PB85-147189

Determining the Stability of Treated Municipal Sludges

Manhattan Coll., Bronx, NY

Prepared for

Environmental Protection Agency, Cincinnati, OH

Jan 85

U.S. Department of Commerce
National Technical Information Service
NTIS

PB85-147189

EPA-600/2-85-001
January 1985

DETERMINING THE STABILITY OF TREATED MUNICIPAL SLUDGES

by

John S. Jeris, Daniel Ciarcia,
Edward Chen, and Miguel Mena

Manhattan College
Bronx, New York 10471

Cooperative Agreement No. CR806809

Project Officer

R. V. Villiers
Wastewater Research Division
Water Engineering Research Laboratory
Cincinnati, Ohio 45268

WATER ENGINEERING RESESARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/2-85-001	2.	3. RECIPIENT'S ACCESSION NO. PB85 147189/AS
4. TITLE AND SUBTITLE DETERMINING THE STABILITY OF TREATED MUNICIPAL SLUDGES		5. REPORT DATE January 1985
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) John S. Jeris, Daniel Ciarcia, Edward Chen, and Miguel Mena		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Manhattan College 4513 Manhattan College Parkway Bronx, New York 10471		10. PROGRAM ELEMENT NO. CAZB1B
		11. CONTRACT/GRANT NO. C.A. CR806809
12. SPONSORING AGENCY NAME AND ADDRESS Water Engineering Research Laboratory, Cin., OH Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268		13. TYPE OF REPORT AND PERIOD COVERED Final
		14. SPONSORING AGENCY CODE EPA/600/14

15. SUPPLEMENTARY NOTES

Contact: J. B. Farrell (513) 684-7645

16. ABSTRACT

The objective of this project was to determine the potential for further biological degradation biologically of municipal sludges which have undergone either little or major treatment. A literature survey was conducted to determine the most fruitful approaches, followed by laboratory scale studies.

The literature survey summarizes available information related to the characteristics and various stability parameters of municipal sludges that have undergone treatment by anaerobic, aerobic or thermal conditioning processes. The laboratory study built upon methods described in the literature for evaluating stability of sludges. Stability of a variety of received sludges was evaluated by measuring response to additional aerobic or anaerobic digestion of long duration, and by cumulative generation of hydrogen sulfide. Responses to aerobic digestion of the as-received sludges were generally similar and showed substantial reductions in parameters such as BOD and COD. Oxygen uptake eventually reached a low stable value. The same kind of reduction in parameters occurred with anaerobic digestion. The hydrogen sulfide generation test generally showed well defined points at which H_2S generation virtually ceased as sludge storage increased. This test shows promise as a method for comparing sludges for potential for further biological decomposition.

Although much has been learned about the response of various parameters indicative of sludge stability to further digestion, a simple measurement indicating sludge stability was not developed.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES 205
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE

EPA Form 2220-1 (9-73)

DISCLAIMER

Although the information described in this article has been funded wholly or in part by the United States Environmental Protection Agency through assistance agreement number CR806809 to Manhattan College, it has not been subjected to the Agency's required peer and administrative review and therefore does not necessarily reflect the views of the Agency and no official endorsement should be inferred.

FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water systems. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. The Clean Water A , the Safe Drinking Water Act, and the Toxics Substances Control Act are three of the major congressional laws that provide the framework for restoring and maintaining the integrity of our Nation's water, for preserving and enhancing the water we drink, and for protecting the environment from toxic substances. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Water Engineering Research Laboratory is that component of EPA's Research and Development program concerned with preventing, treating, and managing municipal and industrial wastewater discharges; establishing practices to control and remove contaminants from drinking water and to prevent its deterioration during storage and distribution; and assessing the nature and controllability of releases of toxic substances to the air, water, and land from manufacturing processes and subsequent product uses. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

This report details the further aerobic and anaerobic biological degradation possible of sludges generated from municipal sources. Raw primary, waste activated, trickling filter and anaerobic digester sludges from full-scale treatment plants were studied.

Francis T. Mayo, Director
Water Engineering Research Laboratory

ABSTRACT

The overall objective of this project was to determine the potential for further degradation biologically of municipal sludges which may have undergone either little or major treatment. This objective was achieved by means of a literature survey to determine the most fruitful approaches, followed by laboratory scale studies.

The literature survey section of this report comprehensively summarizes available information related to the characteristics and various stability parameters of municipal sludges that have undergone treatment by anaerobic, aerobic, or thermal conditioning processes. The starting materials being considered include raw primary sludge, activated sludge, and mixtures of the two. The treatment processes produce sludges that have a broad range of instability associated with them because design factors for the treatment processes from which they are generated vary widely. Many of the parameters considered useful in determining sludge instability are also reviewed in the literature survey.

The laboratory study was built upon methods described in the literature for evaluating stability of sludges. Sludges studied included primary, trickling filter and activated sludges and sludges from full scale anaerobic digesters, heat treatment processes, and aerobic digestion. Stability of these as-received sludges was evaluated by measuring response to additional aerobic or anaerobic digestion, and by cumulative generation of hydrogen sulfide. Responses of the as-received sludges to aerobic digestion were generally similar and showed substantial reductions in parameters such as BOD and COD. Oxygen uptake eventually reached a low stable value for all sludges. The same kind of reduction in parameters occurred in the as-recived sludges with anaerobic digestion. The hydrogen sulfide generation test showed well defined points at which H_2S generation virtually ceased as sludge storage increased but not for all sludges.

Although much has been learned about the response of various parameters indicative of sludge stability to further digestion, a simple measurement indicating sludge stability was not developed.

CONTENTS

Foreword.. iii

Abstract.. iv

Figures... vi

Tables.. xii

Acknowledgement... xv

1. Introduction.. 1

2. Conclusions... 2

3. Recommendations... 3

4. Literature Survey... 4

5. Sources and Types of Municipal Sludges...................... 98

6. Experimental Procedures and Apparatus....................... 107

7. Laboratory Results.. 124

8. Discussion of Results....................................... 173

References.. 180

Appendix 187

FIGURES

Number	Page

1 The Fossilization Pathway of the Carbon Cycle (2) 5

2 Relation Between Raw Sludge Detention Time and Volatile Matter Reduction (23) 5

3 Graph Showing Comparison of Completion of Digestion at High Rate Plants with Accepted Standards 13

4 Anaerobic Digestion Volatile Solids Destruction Vs. Waste Activated Sludge/Primary Sludge Ratio (32) 19

5 Reduction of Organic Matter During First Test at 20°C (1), 30°C (2), and 50°C (3) (22) 20

6 Effects of SRT and Temperature on Volatile Solids Reduction in a Laboratory-Scale Anaerobic Digester (33) 22

7 Volatile Solids Reduction Vs. Temp. (°C) X SRT (Days), (3) 23

8 The Effect of Loading on Gas Production (39) 25

9 Sludge Gas and Methane Production During Prolonged Incubation Time (22) 25

10 Bench Scale Digesters Die-Away Gas Production (Formerly Fed With Raw Primary Sludge From Cedar Creek STP) 26

11 Bench Scale Digesters Die-Away Gas Production (Formerly Fed With Thickened Activated Sludge From Cedar Creek STP) 27

12 Bench Scale Digesters Die-Away Gas Production (Formerly Fed With 70% Raw Sludge Plus 30% Thickened Activated Sludge From Cedar Creek STP) 28

13 Relationship of BOD of Sludge Supernatant to Detention Time (40) 29

BEGIN FIRST LINE OF TEXT HERE
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD: BEGIN SECTIONS HERE
6-1/2"
BEGIN LAST LINE OF TEXT
BOTTOM OF IMAGE AREA OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
3/8"
PAGE NUMBER
EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 2371
TYPING GUIDE SHEET

Number **Page**

14 Filtration Rate Versus Solids Concentration; Leaf Test Data for Primary-Activated Sludge, East Lansing, Mich.; Medium, Polyethylene 802 HF; Vacuum, 20 In. Hg Cycle, 3.6 Min.; Submergence, 25 Percent; Chemicals, 2½ Percent $FeCl_3$ and 10 Percent Lime (48)........ 35

15 Cake Solids as a Function of Feed Solids for Different Sludges (52)........ 36

16 Cake Solids as a Function of Feed Solids for Different Sludges (3)........ 38

17 Chemical Cost as a Function of Yield (52)........ 39

18 Rates of Inactivation of Coxackie-Virus Type B3 in Digester and Controls at pH 7 and 32°C (59)........ 39

19 Rate of Coxackie-Virus Type B3 in Digester and Controls at pH 7 and 35°C (59)........ 39

20 Effect of Temperature on Rate of Loss of Recoverable Poliovirus Infectivity (61)........ 49

21 Effect of Detention Time on Rate of Loss of Recoverable Poliovirus Infectivity (61)........ 50

22 Poliovirus Recovery During Anaerobic Sludge Digestion (61)...... 51

23 Concentration of Coliforms Surviving as a Function of Detention Time (74)........ 51

24 Concentration of Salmonellae Surviving as a Function of Detention Time (74)........ 56

25 Oxygen Utilization Rates (75)........ 56

26 Oxygen Uptake Rate Versus Temperature (76)........ 58

27 Specific Oxygen Uptake Rates at Various Operating Temperatures, Batch Digestion of a 26% Total Volatile Solids Sludge (77)...... 59

28 Oxygen Uptake Rate Vs. Detention Time in Aerobic Digester (44).. 61

29 Maximum Odour Intensity Index Measured During 14 Days of Storage Vs. Detention Time in Aerobic Digester (44)........ 62

30 Oxygen Uptake Rate and Degree of Stability (%) Vs. Temperature in Aerobic Stabilization Unit, Primary Sludge (44)........ 62

Number Page

31 Variation of Performance Parameters with Time for Primary Sludge/Trickling Filter Humus Digested at 20°C (79) 64

32 Undrained Stability Index for Various Operating Temperatures (77) 65

33 Undrained Stability Index for Various Feed Sludge Concentrations. Batch Digestion at 30°C (77) 66

34 Comparison of Specific Oxygen Uptake Rate and Undrained Stability Index for Digestion at 30°C (77) 67

35 Effect of Detention Time on Aerobic Digestion of Activated Sludge (80) 69

36 Volatile Solids Reductions as a Function of Sludge Age 69

37 Kinetics of Aerobic Sludge Digestion (82) 71

38 Reaction Rate K_d Versus Aerobic Digester Liquid Temperatures (3) 72

39 K_d Versus Suspended Solids (83) 73

40 Effect of Temperature and Detention Time on the Volatile Solids Content of Aerated Sludge (84) 73

41 Effect of Sludge Age on VSS Reduction (76) 74

42 Total Volatile Solids Reductions at Various Operating Temperatures. Batch Digestion of a 2.6% Total Volatile Solids Sludge (79) 75

43 Volatile Solids Reduction as a Function of Digester Liquid Temperature and Digester Sludge Age (3) 76

44 Ammonia, NO_2, and NO_3 Versus Detention Time (84) 78

45 Solids, Alkalinity and pH Versus Detention Time (84) 79

46 Kjeldahl-Nitrogen, NO_2 + NO_3-Nitrogen, and Alkalinity Vs. Detention Time (78) 80

47 Observed Ammonia Nitrogen Concentrations at Various Operating Temperatures. Batch Digestion of a 2.6% Total Volatile Solids Sludge (77) 81

EPA Form 2360-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 287)
TYPING GUIDE SHEET

Number Page

48 ATP/VSS Vs. Detention Time (78)........ 83

49 Settling Curves of Heat-Treated Activated Sludge (90)........ 85

50 Effect of Process Temperature on the Fate of Solids During Heat Treatment (90)........ 87

51 Effect of Process Temperature on the Fate of Nitrogenous Compounds (90)........ 88

52 Response of Sludge Filterability to Non-Oxidative Thermal Conditioning (91)........ 88

53 The Conditioning of Activated Sludge by Heat........ 90

54 The Conditioning of Primary/Activated Sludge by Heat (92)........ 91

55 The Conditioning of Humus Sludge by Heat (92)........ 92

56 The Conditioning of Digested Sludge by Heat (92)........ 93

57 The Effect of Solids Concentration on the Specific Resistance of Heat Conditioned Digested Sludge (92)........ 94

58 Continuously Mixed Anaerobic Reactor Schematic........108

59 Schematic Layout of 1.5 Liter Reactor........110

60 Aerobic Reactor Schematic........111

61 Phase I. Anaerobic Reactor Contents........119

62 Phase I. Aerobic Reactor Contents........120

63 Phase II. Anaerobic Reactor Contents........121

64 Phase II. Aerobic Reactor Contents........122

65 Beacon, N.Y. Aerobic Sludge - Aerobic Stability Parameters......133

66 Beacon, N.Y. and Cold Spring, N.Y. Aerobic Sludges - Aerobic Stability Parameters........134

67 Cold Spring, N.Y. Aerobic Sludge - Aerobic Stability Parameters.135

68 Musconetong, N.J. Aerobic Sludge - Aerobic Stability Parameters.136

BEGIN FIRST LINE OF TEXT HERE
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD; BEGIN SECTIONS HERE

Number **Page**

69 Musconetong, N.J.and Stony Point, N.Y. Aerobic Sludge - Aerobic Stability Parameters....137

70 Stony Point, N.Y. (Summer) Aerobic Sludge - Aerobic Stability Parameters....138

71 Stony Point, N.Y. (Winter) Aerobic Sludge - Aerobic Stability Parameters....139

72 Stony Point, N.Y. (Winter) Aerobic Sludge - Additional Aerobic Stability Parameters....140

73 Rockland County, N.Y. Thermal Sludge - Aerobic Stability Parameters....141

74 Rockland County, N.Y. and Poughkeepsie, N.Y. Thermal Sludge - Aerobic Stability Parameters....142

75 Poughkeepsie, N.Y. Thermal Sludge - Aerobic Stability Parameters....143

76 26th Ward, N.Y.C. Anaerobic Sludge - Aerobic Stability Parameters....144

77 26th Ward, N.Y.C. Anaerobic Sludge - Additional Aerobic Stability Parameters....145

78 Jamaica, N.Y.C. Anaerobic Sludge - Aerobic Stability Parameters.146

79 Jamaica, N.Y.C. Anaerobic Sludge - Additional Aerobic Stability Parameters....147

80 Cedar Creek (Unit 1) 25% Primary + 75% Seed - Anaerobic Stability Parameters....156

81 (Unit 2) 25% Cedar Creek Activated Sludge - 75% Seed - Anaerobic Stability Parameters....157

82 (Unit 3) 35% Stony Point + 65% Cedar Creek Seed - Anaerobic Stability Parameters....158

83 (Unit 4) Cedar Creek Seed - Anaerobic Stability Parameters......159

84 (Unit 5) Rockland County Thermal Sludge + 75% Seed - Anaerobic Stability Parameters....160

85 (Unit 6) 25% Poughkeepsie Thermal Treated Sludge + 75% Seed Anaerobic Stability Parameters....161

BEGIN LAST LINE OF TEXT
3/8"
BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
PAGE NUMBER
EPA Form 2360-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 247)
TYPING GUIDE SHEET

Number **Page**

86 (Unit 7) Stony Point Aerobic Sludge - Anaerobic Stability Parameters....162

87 (Unit 8) 26th Ward Anaerobic Sludge - Anaerobic Stability Parameters....163

88 (Unit 9) Coney Island Anaerobic Sludge - Anaerobic Stability Parameters....164

89 (Unit 10) Cedar Creek Anaerobic Sludge - Anaerobic Stability Parameters....165

90 (Unit 11) Oyster Bay Anaerobic Sludge - Anaerobic Stability Parameters....166

91 (Unit 12) Yonkers Anaerobic Sludge - Anaerobic Stability Parameters....167

92 (Unit 13) Yonkers Anaerobic Sludge - Anaerobic Stability Parameters....168

93 Capillary Suction Test and Specific Resistance - Units 1-4......169

94 Capillary Suction Test and Specific Resistance - Units 5-8......170

95 Capillary Suction Test and Specific Resistance - Units 9-12.....171

96 Capillary Suction Test and Specific Resistance - Unit 13........172

97 Lead Acetate - Hydrogen Sulfide Odor Test - Anaerobic Sludges...177

98 Lead Acetate - Hydrogen Sulfide Odor Test - Aerobic Sludges.....178

TABLES

Number		Page
1	Composition and Characteristics of Primary, Activated and Digested Primary Sludge	6
2	Composition of Fresh and Digested Sewage Solids	7
3	Composition of Sewage Solids	8
4	Supernatant Characteristics of Digested Domestic Sludge for Different Detention Times	9
5	Liters of Sludge Produced per Million Liters of Wastewater Treated	9
6	Digestion of Primary and Activated Sludges	11
7	Summary of Operating Results of High Rate Digestion Tanks	14
8	Anaerobic Digestion of 100% Thickened Unox Waste Activated Sludge (31)	17
9	Anaerobic Digestion Summary (32)	18
10	Gas Production for Several Compounds in Sewage Sludge	21
11	Variation of BOD in Sludge Liquor with Storage (41)	31
12	Variation of COD in Sludge Liquor with Storage (41)	31
13	Changes in BOD of the Filtrate from a High-Rate Humus Sludge After Various Conditions of Storage (42)	32
14	Changes in the Chemical Oxygen Demand of the Filtrate from Activated Sludges During First 24 Hrs' Storage at 20°C (42)	32
15	Characteristics of Three Sludges: Particle Sizes and Dewaterability (1)	34
16	Minimum Filter Rates After Chemical Conditioning (50)	40
17	Averaged Vacuum Filtration Performance Data (51)	40

EPA Form 2360-4 (4-80)
TYPING GUIDE SHEET

Number **Page**

18 Typical Dewatering Performance Data for Rotary Vacuum Filters - Cloth Media (3).. 41

19 Typical Dewatering Performance Data for Rotary Vacuum Filters - Coil Media (3).. 42

20 Pathogenic Human Viruses Potentially in Wastewater Sludge (3)... 44

21 Pathogenic Human Bacteria Potentially in Wastewater Sludge (3).. 45

22 Pathogenic Human and Animal Parasites Potentially in Wastewater Sludge (3).. 46

23 Municipal Treatment Plant Killing and Inactivating Pathogens in Sludges.. 47

24 Effect of Sewage Treatment Processes on Indicator and Pathogenic Microbial Populations in Raw Sewage (65)........................ 47

25 Rate of Loss of Recoverable Poliovirus Infectivity at 1.6 kVS/m^3-d (61).. 48

26 Comparison of Methods and Experimental Conditions for Recent Studies on Virus Recovery During Anaerobic Digestion (61,62).... 52

27 Survival in Anaerobic Digesters (68)............................ 54

28 Pathogenic Bacteria in Sludge (1)............................... 55

29 Pathogen Occurrence in Liquid Wastewater Sludges (3)............ 55

30 Lead Acetate Test - Primary Sludge (78)......................... 63

31 Effect of Heating 1 Percent Activated Sludge to Different Temperatures for 1 Hour With and Without Oxygen Present (90).... 86

32 LA/OMA Thermal Pretreatment Studies Comparison of Digester Performance Waste Activated Sludge............................. 96

33 LA/OMA Thermal Pretreatment Studies Laboratory Scale Anaerobic Digestion (Mesophilic) Blend of Primary and Waste Activated Sludge.. 97

34 Summary of Treatment Plant Operational Parameters for the Activated Sludges Used..100

35 Summary of Treatment Plant Operational Parameters for the Thermal Sludges..100

Number **Page**

36 Poughkeepsie, N.Y., Sludge Characteristics....102

37 Summary of Treatment Plant Operational Parameters for the Anaerobic Sludges....103

38 Analytical Methods....115

39 Summary of Parameters - Aerobic Digestion....131

40 Summary of Parameters - Aerobic Digestion of Anaerobic Sludges..132

41 Anaerobic Units....153

ACKNOWLEDGEMENT

I acknowledge with grateful appreciation the contribution of Mrs. Eileen Lutomski for her suggestions and careful typing of the report manuscript. The suggestions and assistance of EPA staff at Cincinnati's Municipal Environmental Research Laboratory, particularly Mr. R. V. Villiers, Mr. B. V. Salotto, and Dr. J. B. Farrell, are also acknowledged.

SECTION I

INTRODUCTION

The major and most offensive by-product of municipal wastewater treatment is sludge. Early in the history of wastewater treatment, processes were developed that ameliorated the obnoxious character of sludge, and permitted its disposal without creating intolerable conditions at the point of disposition. The primary processes for improving the acceptability of (i.e., "stabilizing") sludge are anaerobic and aerobic digestion. Thermal processes also have been utilized in recent years for stabilizing sludge.

A sludge should be stable before final disposal. Unfortunately, the term "stable" is unclear with respect to municipal sludges. Before disposal, a sludge should have been stabilized to an extent where no adverse environmental effect can be easily observed upon disposal. Sludges disposed by means of land application should be sufficiently stable as not to cause odor or health problems. Disposal of sludges into the ocean should not cause adverse effects on the marine ecosystem. It is not within the scope of this report to determine how stable a sludge should be before disposal. It is however our concern to define stability with respect to equilibrium concentrations of various parameters achieved after long term biological digestion.

Sludges originating from aerobic, anaerobic and thermal processes were studied in this project. These sludges in pure form and mixtures were further degraded by means of aerobic or anaerobic digestion. Data obtained during our study illustrates how various parameters behave after prolonged digestion. Since changes occurred in sludge composition after further digestion, were the sludges studied truly stable? It is the hope of the authors of this report to better define stability with respect to municipal sludges through this extensive laboratory work and literature survey.

SECTION 2

CONCLUSIONS

1. Aerobically digested, extended aeration, thermally treated and anaerobically digested primary, activated sludge and trickling filter sludges were not stable with respect to most parameters measured.

2. No single or combined parameter was found to be a standard which would indicate sludge stability. Most sludges reached steady state with most parameters studied in 20 to 40 days.

3. Stability can be traced by monitoring the parameter of interest at a specific treatment plant and then using the value obtained in the field in future applications.

4. A specific oxygen uptake rate of 0.4-1.0 mgO_2/gm VSS-hr may be a good indicator of stabilized aerobically digested sludge. This measurement is not applicable to anaerobic sludges.

5. Capillary suction tests and specific resistance measurements for dewaterability were inconsistent and are not satisfactory as stability indicators.

6. The centrifuge button test appears to be a reasonable indicator of hydrogen sulfide odor formation and is generally completed in 15 to 30 days for most sludges.

7. Total solids, volatile solids, BOD_5 and COD continuously decreased for all sludges until steady state was reached in typically from 20 to 40 days. These measurements are not particularly sensitive analyses of stabilization.

8. pH, alkalinity and conductivity in general did not appear useful as stability indicators; but in conjunction with nitrification and nitrate formation, they may serve as indicators.

9. During anaerobic treatment of anaerobic sludges the rate of gas formation and the concentration of volatile acids decrease rapidly in 5-10 days, but this relationship to stability is not evident.

SECTION 3

RECOMMENDATIONS

1. Continue testing the most promising indicators of sludge stability as determined in this investigation using various municipal sludges, in order to confirm their effectiveness.

2. Extend testing to include sludges from rotating biological contractors, trickling filters and solids from composting operations.

3. Develop and extend the centrifuge button technique for hydrogen sulfide odor production for more universal use, especially in conjunction with treatment plant operation.

4. Continue the development of the ATP and crude fibre analyses.

5. Confirm the use of the specific oxygen uptake rate (SOUR) analyses as an indicator of the stability of aerobically treated sludges.

6. Develop stability and drainability relationships using the capillary suction test.

EPA Form 2350-4 (4-80)
TYPING GUIDE SHEET

SECTION 4

LITERATURE SURVEY

INTRODUCTION

The term "stabilized sludge" is widely used and understood but surprisingly difficult to define. Vesilind (1) has suggested that a stable sludge is one that can be disposed of without damage to the environment, and without creating nuisance conditions. Damage was defined as an undesirable rate or method of degradation, or the toxic effect on existing ecology. Nuisance was considered simply an affront to the senses of sight or smell. Based on these definitions, he proposed many parameters such as odor, toxicity, reduction in volatile solids, and others to define sludge stability. A scientific approach to defining stable sludge was presented by Hartenstein (2) and is shown in Figure 1. Digested anaerobic and aerobic sludges are shown in the upper right hand corner of the figure. As sludges become stable they move toward the bottom left hand corner. In stabilization, the sludges oxygen to carbon and hydrogen to carbon ratios approach zero. In this process however many intermediary compounds of increasing stability are formed. Hartenstein suggests that a sludge is stabilized when it has been humified as it appears to be non-putrescible at this stage of decomposition.

EPA's recent sludge treatment and disposal manual (3) indicates the principal purpose of stabilization is to make the treated sludge less odorous and putrescible as well as to reduce the pathogenic organism content. The required stability of sludge depends primarily upon the final disposal method selected. For example, if the sludge is to be dewatered and incinerated, frequently no stabilization procedure is employed, but if the sludge is to be applied to agricultural lands, highly stabilized sludge with minimum amounts of toxic materials, pathogens and odor generation potential should be considered. Therefore, the determination of the degree of sludge treatment or the instability of sludges is very important in terms of the ultimate disposal.

The purpose of this literature survey is to summarize the available information that is related to the characteristics and various stability parameters of municipal sludges that have undergone treatment by anaerobic, aerobic or thermal conditioning processes. Sludges, being considered, include raw primary sludge, activated sludge, and mixtures thereof. These sludges have a broad range of instability not only because of their different characteristics but also due to the various process factors on which they are designed. It is the condition of the product sludge that is of major interest in this study. The parameters studied in this review were

TYPING GUIDE SHEET
FIRST LINE OF TEXT HERE
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD: BEGIN SECTIONS HERE

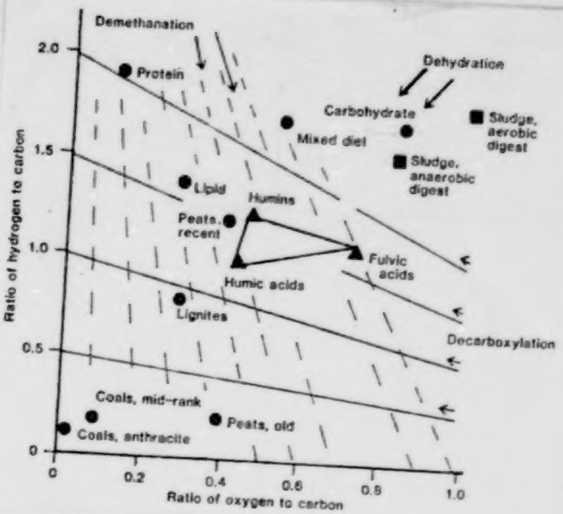


FIGURE 1 - THE FOSSILIZATION PATHWAY OF THE CARBON CYCLE (2)

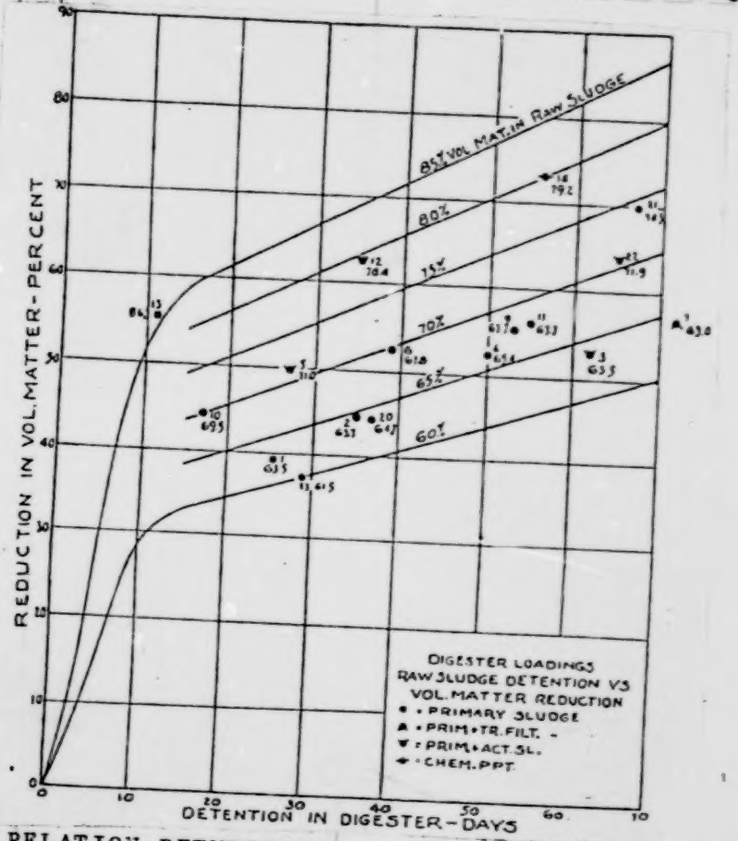


FIGURE 2 - RELATION BETWEEN RAW SLUDGE DETENTION TIME AND VOLATILE MATTER REDUCTION (23)

BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
BEGIN LAST LINE OF TEXT
3/8"
EPA-287 (Cin.)
(4-76)
PAGE NUMBER

TABLE 1. COMPOSITION AND CHARACTERISTICS OF PRIMARY, ACTIVATED AND DIGESTED PRIMARY SLUDGE

Item	Primary			Activated			Digested Primary		
	Range	Typical	Ref	Range	Typical	Ref	Range	Typical	Ref
Total Solids, %	2-7	4	(4)	0.83-1.16		(4)	6-12*	10	(4)
Volatile Solids, (%TS)	40-80	65	(4,5)	65-79 61-75 65-75 59-70		(4) (6) (5) (7)	30-60	40	(4)
Total Ash. %	20-40	-	(5,8)	25-38		(5,8)	40-55	-	(8)
Spec.Grav.of Sludge	-	1.02	(4)		1.005	(4)	0.95-1.03	-	(4)
Grease & Fats, (%TS)	7-35 6-30	- -	(7,9) (4)	5-12 -		(5,8)	5-20	-	(4)
Hemicellulose, (%TS)	-	3.2	(5,9)	-			-	1.6	(5)
Cellulose (%TS)	- 8-15	3.8 10	(5,8) (4)		7.0	(7,8)	8-15	10	(4)
Lignin	-	5.8	(5,9)	-			-	8.4	(5)
Protein (%TS)	20-30 22-28	25 -	(4) (5,9)		32.4 37.5	(8) (5)	15-20 16-21	18	(4)
Nitrogen (N,%TS)	1.5-4.0	2.5	(4,9)	2.4-5.0	-	(4,7)	1.6-6.0	3	(4,7)
Phosphorus (P_2O_5%TS)	0.8-2.8	1.6	(4)	2.8-11	-	(4,7)	1.5-4.0	2.5	(4,7)
Potash (K_2O%TS)	0-1.0	0.4	(4)	-	-		0-3.0	1.0	(4)
Iron (not as $S^=$)	2-4	2.5	(4)	-	-		3-8	4.0	(4)
Silica(S_iO_2,%TS)	15-20	-	(4)	-	-		10-20	-	(4)
pH	5-8	6	(4,7)	6.5-7.5		(4,7)	6.5-7.5	7.0	(4,7)
Alk.(mg/l as $CaCO_3$)	500-1,500	600	(4)	580-1,100		(4)	2,500-3,500	3,000	(1)
Vol.Acids(mg/l as HAc)	200-2,000	500	(4)	1,100-1,700	-	(4)	100-600	200	(4)
Thermal Content (Kilocal/Kg)	3,780- 5,560	4,220	(4)	3,630	(10)		1,500- 3,780	2,220	(4)

EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 2ET)
TYPING GUIDE SHEET

useful in determining a suitable instability index. This information served as a guide in the laboratory aspects of the project.

SLUDGE COMPOSITION AND CHARACTERISTICS

The characteristics of sludge may vary depending on its origin, its age, and the type of processing to which it has been subjected. Primary sludge, from domestic wastewater, drawn from the bottom of primary settling tanks will contain about 4 to 5 percent total solids. Most often it has undergone practically no decomposition and is highly unstable and putrescible. Physical, chemical and biological analysis of primary sludge indicates that it is usually grey-brown in color, slimy, extremely malodorous, and does not drain well on drying beds; but can be dewatered mechanically. It contains water, inorganic compounds, organic compounds (carbohydrates, fats, and proteins) as well as viruses, bacteria, protozoa and metazoa. The volatile matter accounts for approximately 60 to 80 percent of the total solids. In general, primary sludge can be readily digested under suitable conditions of operation and is easier to manage than biological and chemical sludges. Typical data on the composition and characteristics of untreated and digested sludges are reported in Table 1.

Substrate composition is basic to any biological process. A number of workers have studied sewage sludges extensively in an attempt to describe average composition. Buswell and Neave (11) analyzed 39 samples of fresh and digested sewage solids and their results are given in Table 2.

TABLE 2. COMPOSITION OF FRESH AND DIGESTED SEWAGE SOLIDS

Constituent	Fresh Sewage Solids (% of dry Weight)	Digested Sewage Solids (% of dry Weight)
Grease (petroleum ether)	25.2	6.9
Crude fiber	10.8	9.8
Humic acid (pyridine soluble)	4.0	8.6
Total	59.4	37.8
Volatile matter by analysis	60.9	39.6

Heukelekian (12) later considered the composition of sludge and presented an approximate analysis which is given in Table 3.

EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 287)
TYPING GUIDE SHEET

TABLE 3. COMPOSITION OF SEWAGE SOLIDS

Constituent	Fresh Sewage Solids (% of dry Weight)	Digested Sewage Solids (% of dry Weight)
Soluble in ether	34.40	8.18
Soluble in cold and hot water	9.52	5.48
Soluble in alcohol	2.49	1.59
Hemicellulose	3.20	1.58
Cellulose	3.78	0.56
Lignin	5.78	8.37
Crude protein	27.12	19.68
Ash	24.13	56.00
Total	110.42	101.44

He also reported that about 68 percent of the volatiles in fresh sewage solids were made up of 19.13 percent ether solubles, 25.08 percent total nitrogenous matter, and 23.56 percent carbohydrates on a dry basis.

Supernatant characteristics from digesters may contain concentrated organic loads which are frequently returned to the primary settling tank or to the aerators. Table 4 gives typical supernatant concentrations for a number of hydraulic detention times.

Activated sludge in municipal secondary treatment plants varies in the amount of organic and inorganic material, and thus has variable physical properties. The organic component of the floc consists extensively of organisms, the amount of which can be expressed in terms of organic nitrogen or volatile matter. The inorganic component consists of different elements, including sodium and potassium which can be a part of the cells. But these elements typically do not reach high values. Most of the inorganic material consists of a limited number of elements e.g. silicon, aluminum, calcium and phosphorous. Activated sludge has a yellow-brown fluffy appearance, an inoffensive odor, is difficult to dewater and very active biologically. Typical data on the composition and characteristics of activated sludge is also reported in Table 1.

The anaerobic digested sludge has dark brown to black color and contains a large amount of gas. Well digested sludge has a musty odor that is not at all objectionable. Anaerobic digestion usually results in approximately a 50% reduction of volatile solids, (Table 1) and a significant destruction of pathogenic organisms. Digested sludge can be disposed of directly on land, or dewatered on drying beds or by mechanical means before ultimate disposal.

EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 337)
TYPING GUIDE SHEET

TABLE 4. SUPERNATANT CHARACTERISTICS OF DIGESTED DOMESTIC SLUDGE FOR DIFFERENT DETENTION TIMES

Parameter	Detention Time, Days 90	60	30	20	10	5
pH	7.51	7.47	7.45	7.28	6.33	5.15
Alkalinity, mg/l as $CaCO_3$	4 991	4 640	4 484	4 295	3 353	2 075
NH_3-Nitrogen mg/l as N	1 215	1 079	1 029	938	921	518
Total volatile acids, mg/l as acetic acid	37	324	721	1 405	3 972	5 519
% Butyric acid	2.56	9.88	9.49	15.00	24.85	25.17
% Propionic acid	3.23	23.23	28.00	26.17	35.78	39.91
% Acetic acid	59.31	63.05	61.66	47.56	38.55	34.10
% Formic acid	20.84	2.11	0.54	0.67	0.51	0.43
% Lactic acid	14.06	1.24	0.33	0.60	0.11	0.40
Settleable solids, BOD_5,mg/l	1 464	1 738	3 036	6 081	8 527	11 014

Included in Table 1 is the thermal content of various sludges. The thermal content of sludge is important where incineration or some other combustion process is considered. Accurate bomb-calorimeter tests should be conducted so that a heat balance can be made for the combustion system. The thermal content of untreated primary sludge is the highest, especially if it contains appreciable amounts of grease and skimmings.

Table 5 shows some typical average sludge production rates for comparison. It is emphasized that the designer should be very careful in calculating the sludge quantities considering the increased contributions from industry.

TABLE 5. LITERS OF SLUDGE PRODUCED PER MILLION LITERS OF WASTEWATER TREATED

Raw Primary Sludge	Waste Activated Sludge	Ref.
2,950	19,400	(13)
3,530	14,600	(14)
2,440	18,700	(15)
3,000	19,400	(16)

EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 267)
TYPING GUIDE SHEET

The characteristics, concentration and quantity of sludges produced in wastewater treatment can vary tremendously from plant to plant because of the difference in types of wastewaters, and in the design and operation of wastewater treatment plants. It is, therefore, necessary to obtain as much information as possible on the nature of different sludges before studying the parameters of sludge instability.

ANAEROBICALLY DIGESTED SLUDGE

Anaerobic digestion is a treatment process employing facultative and strictly anaerobic bacteria to decompose organic matter in wastewater. Proper application of this process results in virtually complete destruction of putrescible organics, significant reduction in pathogens, conversion of hydrophilic solids to water, minerals, methane and carbon dioxide gases and a humus-like residue. The anaerobic digestion process can improve the dewaterability of the sludge. Rapidly increasing energy costs have made the methane production aspect of this process more important. The major drawback of this process is its reputation as an inherently unstable, difficult to control process. This reputation may be unjustified. Many problems with anaerobic digestion may be the result of improper operation and maintenance.

The loss of volatile solids is an accurate measure of the loss of mass of solids of the sludge. The importance of this measure and the ease with which the volatile solids test is carried out have made volatile solids reduction the most important parameter indicating the changes in sludge that take place during anaerobic and also aerobic digestion. Other parameters relating to changes taking place in digestion are frequently related to this parameter.

One of the major objectives of anaerobic digestion is to decompose the highly putrescible organic solids present in municipal wastewater by conversion to relatively stable or inert organic and inorganic compounds. Thus the amount of solids for ultimate disposal can be reduced significantly. The degree of volatile solids reduction in anaerobic digestion depends on the characteristics of the sludge and the operating parameters of the digestion system such as solids retention time, temperature, etc. In a controlled anaerobic digester, the volatile solids reduction increases with the solids retention time until it reaches 50 to 60 percent reduction. Beyond this point, further reduction is minimal even with substantial increase in solids retention time because only 60 to 80 percent of the volatile solids in municipal wastewater sludge is biodegradable; the remaining fraction consists mainly of inert organics such as lignin and tannins. Rudolf (17) incubated sludge samples for long-time digestion experiments and found that during 203 days of incubation the volatile matter was reduced by 67-70 percent. Another long-term experiment showed that volatile matter reduction in five and one-half years amounted to 72.3 percent. He concluded that within a reasonable time, volatile matter reduction rarely exceeds 70 percent under most carefully controlled conditions, and a 50 percent volatile solids reduction can be considered satisfactory. Some of the volatile substances decompose more readily such as some fatty substances and certain cellulosic compounds. In the 203 days retention time study, cellulose disappeared almost completely. From 84 to 87 percent of the ether-soluble material was destroyed and total carbon was reduced 68 to 75 percent.

Greases are of interest because normally they account for about 30 percent of the volatile matter in raw wastewater sludge (18). However, over 50 percent of the chemical oxygen demand reduction and methane production during anaerobic digestion occurs as a result of grease degradation. Studies by Sawyer (19) and McCarty (20) have shown that these materials are degraded more slowly than the bulk of sludge volatile matter. Therefore, the rates of degradation of the major components of the grease fraction may be an important factor in determining the detention time required for a digester.

Woods (21) studied the digestibility of lipids, carbohydrates, proteins and volatile solids of primary and activated sludge mixtures in a two-stage digestion system for a total detention period of 78 days. His results indicated a conversion of more than 80 percent of the lipids and carbohydrates into simple compounds was accomplished during the first stage of digestion of 38 days. Volatile solids reduction reached a high of 60 percent, in addition, approximately 38 percent and 27 percent of the proteins were hydrolyzed during the first and second stage of digestion, respectively. Maly (22) also studied the digestibility of mixtures of primary and activated sludge at different temperatures for long periods of time. Table 6 gives the mean decomposition of particular components of organic matter in sludge digested at 30°C for 106 days.

TABLE 6. DIGESTION OF PRIMARY AND ACTIVATED SLUDGES

Parameter	Percent Reduction
Volatile matter (%)	49.4
Fats (%)	64.9
Proteins (%)	57.9

The organic fraction in the sludge is the most likely cause of odor and also makes sludge handling and dewatering difficult. Therefore, the measurement of volatile solids reduction is one of the most important parameters indicating the instability of sludge. Rankin (23) studied the annual operation records of about 20 representative municipal plants (Figure 2) and concluded that the percentage reduction in volatile matter will vary with the original volatile content and retention time. The curves in Figure 2 were derived from data on tanks operating at temperatures in the range of 29.5 to 35°C, with only natural circulation and very little agitation. Solids detention time under these conditions were concentrated between 30 to 70 days and the sources of sludges differed widely. However, in spite of these differences, it seems that a close relationship does exist. Further, the high rate of reduction of volatile matter projected in the first ten days is especially significant.

Estrada (24,25) further studied data from 20 municipal plants with high-rate organic loadings ranging from 1.60 to 4.00 kg volatile solids per day per cubic meter (0 10-0.25 lbs VS/cf-d) digester volume. The types of mixing, raw sludge volatile solids concentration, retention time, and the volatile solids reduction are listed in Table 7. In high-rate digestion systems it is obvious that satisfactory volatile solids reduction can be achieved in a much shorter detention time compared with the conventional digestion system. In Figure 3 volatile solids reduction is plotted against percent volatile solids in the raw sludge. Downes' (26) curve, shown in Figure 3, was derived from a number of sludges obtained from different parts of the country and predicts the degree of digestion based on the relationship between percent destruction of volatile matter and percent volatile matter in the raw sludge.

Schlenz's (27) curve represents the data from 13 full scale treatment plants using values, based upon each operator's judgement, as to the detention time the operator determined necessary to yield a sufficiently well-digested sludge. The Chicago Pump Company curve is designated for use when forecasting results of the active digester and does not include carry-over digestive action taking place in the storage portion of the tank system. In the unheated storage tank this carry-over digestion amounts to approximately an additional 10 percent reduction of volatile matter. When an additional 10 percent reduction is added to the Chicago curve criteria, it approximates the Downes curve criteria (26). The large scatter of data points attained by the 20 high-rate plants do not give a conclusive relationship between volatile solids reduction and percent volatile solids in raw sludge, probably because of the varying sludge characteristics and operating parameters. However, there is no doubt that the original content of volatile solids greatly influences the percent reduction of such solids that is necessary to obtain a well digested sludge. It should be noted when estimating the reduction of solids of a sludge with low volatile solids, a lower percentage reduction is obtained than that of a raw sludge with high volatile solids. For example, by applying Schlenz's curve, a raw sludge with 65 percent volatile solids yields a volatile solids reduction of approximately 54 percent to produce a resultant digested sludge as stable as a sludge which originally contained 75 percent volatile solids but requires a volatile solids reduction of 73 percent by digestion to reach stability.

Primary, Waste-Activated, and Mixtures of the Two Sludges

Waste activated sludge has been blamed for the difficulties in reducing volatile solids, creating foaming problems, as well as the poor thickening and dewatering characteristics in digested sludge (28,29). Jeris (30) working with bench scale digesters with 20 and 30 days detention time studied sludges taken from the Cedar Creek, New York wastewater treatment plant and reported an average volatile solids destruction of 39 percent for thickened activated sludge, 56 percent for raw primary sludge, and 55 percent for the mixture of raw primary and thickened activated sludge at a ratio of 7:3 by volume. The volatile solids in raw primary and waste activated sludge, before digestion, were 81.6 and 82.2 percent respectively. Following the experiment, he stopped feeding the digesters and observed the volatile solids reduction and gas production of the digested sludges for 151 days with or without mixing. The average volatile solids destruction at the end of the observation included: raw sludge 67 percent, activated sludge 48 percent, and the mixture of the two, 64 percent. Actually, the volatile solids con-

FIRST LINE OF TEXT HERE
TYPING GUIDE SHEET
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD; BEGIN SECTIONS HERE

1, HARTFORD, CONN.
2, WILMINGTON, DEL.
3, ARLINGTON, VA.
4 a b c, SAWYER-PILOT
5, MORGAN - PILOT
6, ERIE, PA.
7, COLUMBUS, OHIO
8, ABINGTON, PA.
9, GRAND RAPIDS, MICH
10, TRACY, CAL.
11, BERGAN, N. J.
12, BOWERY BAY - PILOT
13, BOWERY BAY
14, MIDDLEBORO - PILOT
15, GREENWICH - PILOT
16, RIVERSIDE - PILOT
17, AURORA, ILL.
18, SALT LAKE CITY
19, ROCKFORD, ILL.
20, KEEFER - PILOT

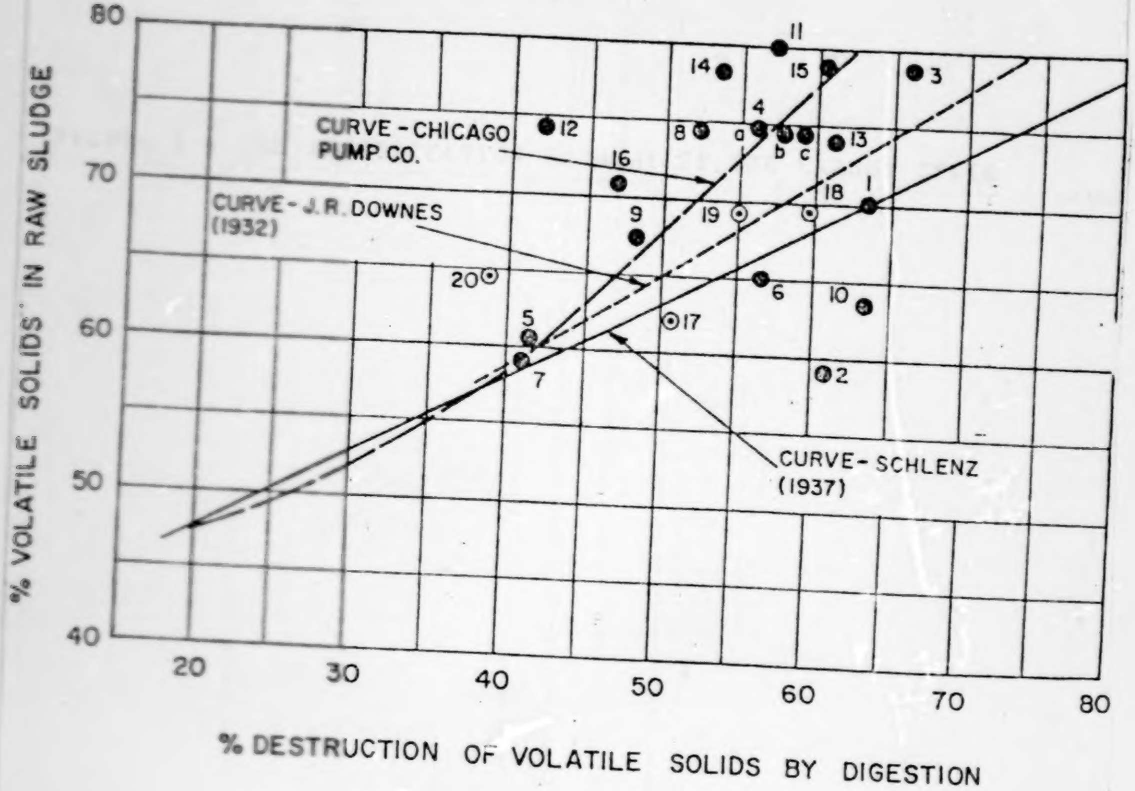


FIGURE 3 - GRAPH SHOWING COMPARISON OF COMPLETION OF DIGESTION AT HIGH RATE PLANTS WITH ACCEPTED STANDARDS (25)

LAST LINE OF TEXT
BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
3/8"
PAGE NUMBER
EPA-287 (Cinc.)
(4-76)

TABLE 7. SUMMARY OF OPERATING RESULTS OF HIGH RATE DIGESTION TANKS

Index	Plant	Type of Agitation	Period of Test Months	Raw Sludge % Solids	Raw Sludge % V.M.	Loading Kg VM/day-Cubic Meter	Retention No. of Days	Digested Sludge % Red. V.M.
1	Hartford, Conn.	Pearth	1	7 *	69.4	2.80	18	63
2	Wilmington, Del.	"	3	6	59.0	1.62	22.5	61
3	Arlington, Va.	"	9	4.5	79.0	3.56	12	66
4a	Sawyer-Pilot	Gas. Rec.	2.5	4.42	74.5	3.36	10	55.8
b	" "	" "	"	"	"	2.24	15	57.2
c	" "	" "	"	"	"	1.60	20	58.2
5	Morgan-Pilot	C.R.P.	12	7.37	60.5	4.20	10.1	41.5
6	Erie, Pa. (54)	"	12	2.8*	65.5	2.00	9.6	56.5
7	Columbus, O.	"	10	6.6	59.2	2.63	13.9	40.4
8	Abington, Pa.	"	2	3.3*	74.4	1.89	13.3	51.8
9	Grand Rapids, Mich.	"	12	4.6	67.3	2.19	14.8	48
10	Tracy, Calif.	"	5	6.0	68.4	1.95	19.8	63.5
11	Bergen Co., NJ	Mech.**	12	3.1*	80.0	1.74	15.7	57.3
12	Bowery Bay, NY Pilot Plant	Mech.	6	5.1	74.5	2.88	13.3	42.5
13	Bowery Bay, NY	None	8	10.2	74.1	2.61	31.0	61

continued on next page

TABLE 7. (cont'd)

Index	Plant	Type of Agitation	Period of Test Months	Raw Sludge % Solids	Raw Sludge % V.M.	Loading Kg VM/day-Cubic Meter	Retention No. of Days	Digested Sludge % Red. V.M.
14	Middleboro, Mass. Pilot Plant	Mech.(Dorr)	5.5	8.2	78.0	3.20	22.0	53.9
15	Greenwich, Conn. Pilot Plant	" "	2	8.7	78.5	3.84	18.8	60.8
16	Riverside, Calif. Pilot Plant	" "	2	7.6	70.9	2.08	25.5	47
17	Aurora San.Dist. Aurora, Ill.	W.P.E. Gas-lifter	8	4.9	62.9	2.10	15.1	51
18	Salt Lake City Suburban San.Dist.	"	2 (a)	6	68.9	1.76	23	54
19	Rockford, San.Dist. Rockford, Ill.	"	2	5.9	69.5	2.23	18.3	51
20	Keefer-Pilot	Pre-mixing(b)	2.5	4.8	69.4	3.78	8.8	38.5
21	Jamaica, L.I.	Mech.(Dorr)	17	6.8	73.3	4.00 (c)	12.5	52

(a) Typical of about a year's operation experience.
(b) Pre-mixing of raw and digested.
* Computed by Author
** Agitated by use of Recirculating Pumps
(c) Recommended loading by Authors and results of August 1959 when this loading was carried out.

centrations remained fairly constant from the 67th day. By this time the sludges had apparently stabilized.

The County Sanitation District of Los Angeles County also conducted an extensive investigation on the digestibility of 100 percent waste activated sludge in pilot digesters. Table 8 (31) shows the digester volumes, the monthly average data of volatile solids destruction, raw sludge characteristics and operating conditions. The digester temperature was controlled in the mesophilic range with an average of 34.4°C. The organic loading was in the range of 0.96-1.44 kg volatile solids per day per cubic meter (0.06-0.09 kg VS/cf-d) digester volume. Sludge characteristics remained fairly constant during the period of study. The monthly average volatile solids destruction ranged from 22.2 to 46.2 percent with a median value of 38 percent. It is interesting to note that the average volatile solids reduction is comparable to Jeris' (30) results where both used similar operating conditions. In another pilot study, conducted by Austin et al. (32) on 100 percent waste activated sludge, they concluded that under mesophilic operation (33.9°C), anaerobic digestion destroyed an average of 32 percent of the applied total volatile solids and yielded 0.924 cubic meters of total gas per kilogram (14.8 cf/lb) of volatile solids destroyed. An average hydraulic detention period of 22 days and a daily volatile solids loading of 1.36 kg per cubic meter (0.085 lbs/cf) were maintained.

Digestion of various ratios of combined primary and waste activated sludge were also studied (32). Table 9 summarizes the anaerobic digestion results evaluated at the Saugus-Newhall Water Reclamation plant. The volatile solids reduction data were plotted in Figure 4 versus the waste activated sludge to primary sludge ratio. Jeris' data were also included for comparison. Volatile solids destruction in excess of 50 percent were consistently obtained for all of the combined sludge ratios. Digestion of 100 percent waste activated sludge produced volatile solids destruction of 39 to 50 percent. For 100 percent primary sludge, the volatile solids destruction was 56 to 62 percent.

All of the anaerobic digestion studies conducted to date indicate that waste activated sludge does not digest as well as primary sludge. Since a considerable amount of stabilization has already taken place within the aeration reactor, the biodegradable fraction of these sludges is lower than primary sludge. Consequently, the volatile solids reduction associated with anaerobic digestion is also lower.

Parameters of Sludge Instability

Potential parameters for measuring instability of anaerobically digested sludge include volatile solids, gas production, BOD and COD, filterability, odor production, and pathogen reductions. The following sections review these parameters.

Temperature and Detention Time

The most important operating parameters affecting volatile solids reduction are detention time and digestion temperature. As shown in Figure 5 (22), a mixture of primary and waste activated sludges were digested for a long period of time (186 days) at temperatures of 20°, 30°, and 50°C, with

TABLE 8. ANAEROBIC DIGESTION OF 100% THICKENED UNOX WASTE ACTIVATED SLUDGE (31)

	Oct-Dec 1978	Jan-Mar 1979	Apr-June 1979	May 1979		June 1979		July 1979		Aug 1979	Sep 1979	Oct 1979	Nov 1979	Dec 1979	Jan 1980
Dig. No.	1	1	1	1	2	1	2	1	2	2	2	2	2	1	1
Dig. Vol. (m^{3}3)	37.9	37.9	37.9	37.9	45.4	37.9	45.4	37.9	45.4	45.4	45.4	45.4	45.4	37.9	37.9
Temp. (°C)	34	34	34	34	34	34	35	34	36	37	36	33	33	34	34
Loading (kgVS/ m^3-day)	1.18	1.06	1.13	1.40	1.33	1.06	1.06	1.30	1.17	1.15	.90	1.30	.91	.98	1.14
Detention Time(days)	25	30	27.6	23.8	25	28.2	27.9	26.3	29.3	25	31	25	27.6	26	22
TS in raw activated sludge (%)	3.7	4.0	4.1	4.2	4.2	3.9	3.9	4.5	4.5	3.8	3.6	4.2	3.3	3.2	3.1
VS in raw activated sludge (%TS)	80	79	77	79	79	76	76	76	76	76	77	77	77	79	81
% VS Destroyed	37.7	46.2	41.9	42.0	38.0	40.3	35.7	44.0	35.0	22.2	26.7	35.0	27.7	41.0	43.0

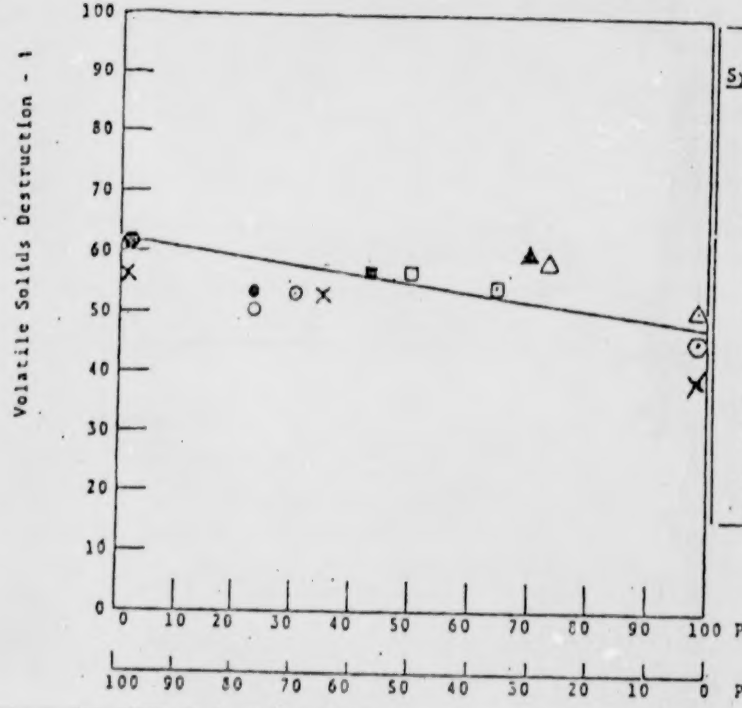
TABLE 9. ANAEROBIC DIGESTION SUMMARY (32)

Location	(% WAS[1] - % primary)	Detention Time (days)	Volatile Solids Loading (kg/m^3-day)	Volatile Solids Destruction (%)	Unit Total Gas Production m^3/kg vs. destroyed
Saugus-Newhall	0 - 100	58	0.67	62	0.94
Saugus-Newhall	23 - 77	32	1.17	53	*
Valencia	23 - 77	43	0.96	50	*
Valencia	31 - 69	20	1.34	54	*
Saugus-Newhall	43 - 57	24	1.36	57	0.87
Saugus-Newhall	50 - 50	19	1.67	57	*
Saugus-Newhall	64 - 36	28	1.30	54	*
Saugus-Newhall	70 - 30	23	1.92	60	0.69
Saugus-Newhall	73 - 27	23	1.69	59	*
Saugus-Newhall	100 - 0	46	0.96	51	0.69
Saugus-Newhall	100 - 0	21	2.00	45	*

*gas data scarce and questionable.

[1] waste activated sludge.

EPA Form 2350-4 (4-80)
TYPING GUIDE SHEET



Symbol	Detention Time (days)	Loading lbsVSS/ft^3-day	Location
⊕	57.8	0.042	Saug-Nhl
●	31.6	0.073	Saug-Nhl
○	43.0	0.060	Valencia
⊙	20.0	0.084	Valencia
■	24.1	0.085	Saug-Nhl
□	19.0	0.104	Saug-Nhl
⊡	28.4	0.081	Saug-Nhl
▲	23.0	0.120	Saug-Nhl
△	22.6	0.105	Saug-Nhl
△	45.9	0.060	Saug-Nhl
◯	21.1	0.125	Saug-Nhl
X	25	0.109	Jeris (30)

FIGURE 4 - ANAEROBIC DIGESTION VOLATILE SOLIDS DESTRUCTION VS. WASTE ACTIVATED SLUDGE/PRIMARY SLUDGE RATIO (32)

EPA-287 (Cin.)
(4-76)

BEGIN FIRST LINE OF TEXT HERE
TYPING GUIDE SHEET
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD; BEGIN SECTIONS HERE

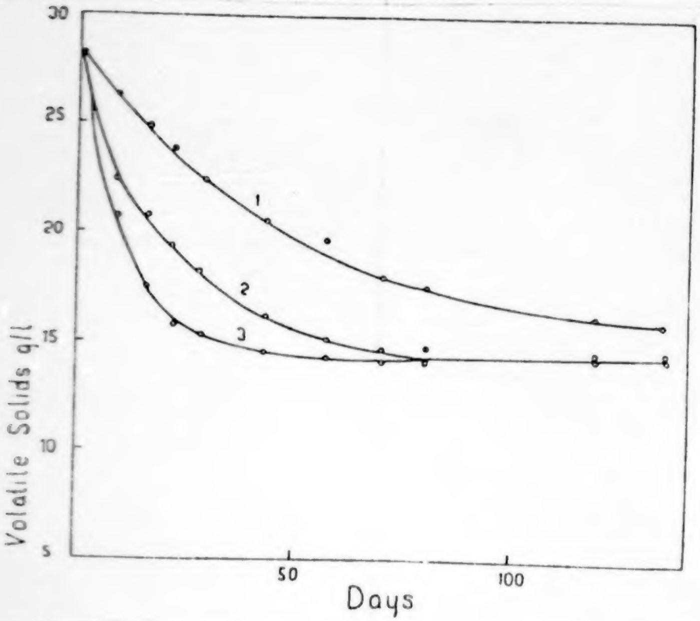


FIGURE 5 - REDUCTION OF ORGANIC MATTER DURING FIRST TEST AT 20°C (1), 30°C (2), AND 50°C (3) (22)

BEGIN LAST LINE OF TEXT
BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
3/8"
PAGE NUMBER
EPA-287 (Cin.)
(4-76)

the final reduction of organic matter reaching 49, 53, and 54 percent respectively. The low volatile solids reduction achieved was probably caused by the low volatile solids present in the raw sludge (50%). The time necessary for satisfactory digestion was as follows: at 20°C, 80 to 100 days; at 30°C, 33 to 50 days; at 50°C, 20 days. Temperature seems to have a strong influence on volatile solids reduction at the initial stage of digestion, as the detention time increases, the temperature effect is less pronounced. Similar effects of solids retention time (SRT) and temperature on volatile solids reduction studied by O'Rourke (33) is shown in Figure 6. For temperatures greater than 20°C, volatile solids reduction climbs rapidly to 50 to 60 percent as the SRT increases. It is noted that the raw sludge had very different characteristics than the one used by Maly and Fadrus (22).

BEGIN LAST LINE OF TEXT HERE
BOTTOM OF IMAGE AREA; OUTSIDE
DROPPED HEAD; BEGIN SECTIONS HERE

The combined effect of SRT and temperature on volatile solids reduction for primary, activated, and mixtures of these sludges is plotted in Figure 7 (3). Although the data points are somewhat scattered, they suggest that primary sludge degrades faster than a mixture of primary and wasteactivated sludge, which, in turn, degrades faster than straight activated sludge.

Gas Production

One of the major advantages of anaerobic digestion is the much smaller amount of biological solids produced per unit of organic material consumed than in aerobic systems. This is the result of the high energy end product, methane. Methane has a definite economic value as a fuel, and is used as a source of energy for both heat and power in many installations. In a well-operated digester, about 0.75-1.2 cubic meters (12-20 cf/lb) of gas can be produced from each kg of volatile matter destroyed (34,35,36,37,38). If the volatile content of the raw sludge is reduced by 50 percent, gas yield should be about 0.37-0.62 cubic meters per kg (6-10 cf/lb) of volatile matter added. Digester gas contains about 65-70 percent methane and 30-35 percent carbon dioxide (21). Carbon dioxide in excess of 35 percent may be an indication that the digestion process is not proceeding properly. The production of gas in a sludge digester comes from the breakdown of organic matter by microorganisms. Both sludge characteristics and operating parameters are important factors influencing gas production. Table 10 shows some specific gas production values for the anaerobic digestion of fats, scum, grease, crude fibers and protein.

TABLE 10. GAS PRODUCTION FOR SEVERAL COMPOUNDS IN SEWAGE SLUDGE

Material	Specific Gas Production cu m/kg destroyed	CH_4 Content, Percent
Fats	1.12-1.44	62-72
Scum	.87-1.00	70-75
Grease	1.06	68
Crude Fibers	.81	45-50
Protein	.75	73

Fatty substances have a higher energy content per unit weight than other forms of organic matter. Thus, the breakdown of a sludge with a high propor-

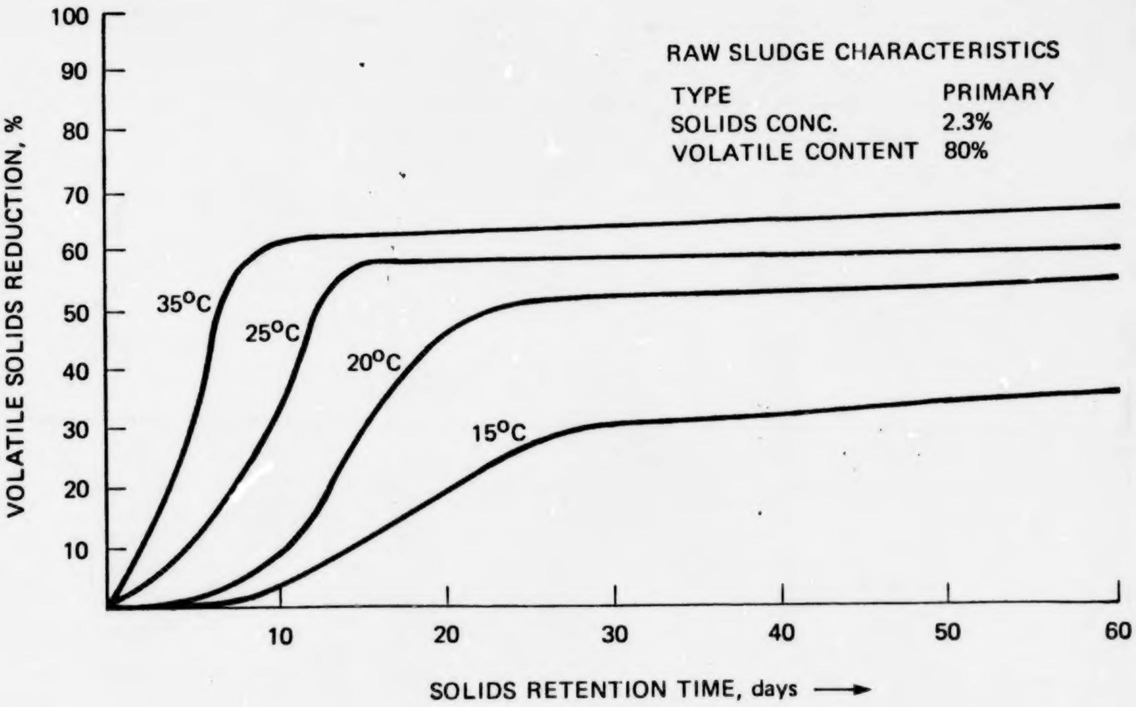


FIGURE 6 - EFFECTS OF SRT AND TEMPERATURE ON VOLATILE SOLIDS REDUCTION IN A LABORATORY-SCALE ANAEROBIC DIGESTER (33)

EPA-287 (Cin.)
(4-76)

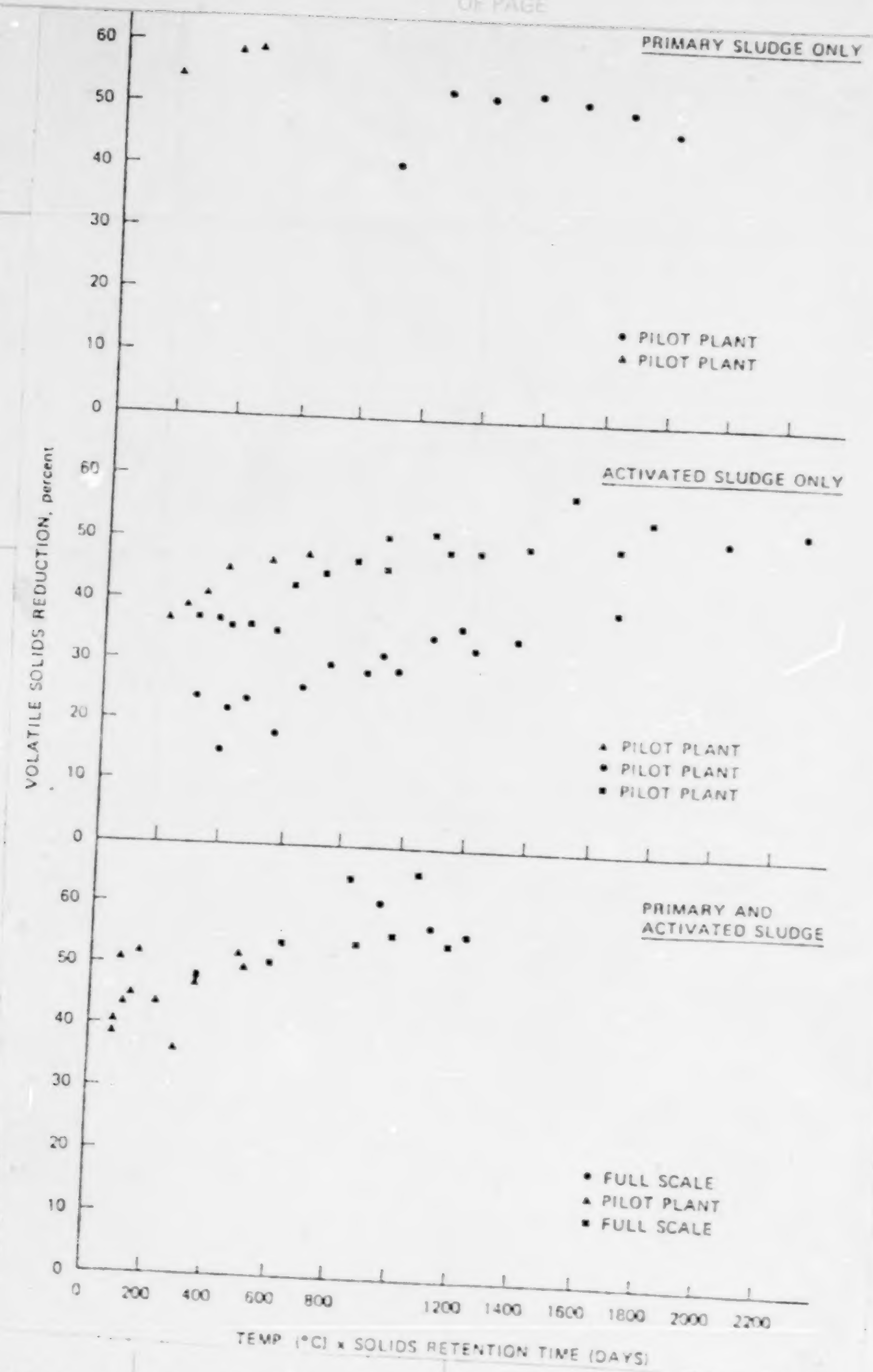


FIGURE 7 - VOLATILE SOLIDS REDUCTION VS. TEMP. (°C) X SRT (DAYS), (3)

EPA-287 (Cin.) (4-76)

tion of fats, oils, and greases can be expected to yield a greater quantity of gas per unit of solids destroyed (3).

Figure 8 shows the effects of temperature and loading on methane and total gas production (39). The curve for methane production is almost horizontal which indicates that loading, in the range of the study, and methane production per unit of volatile solids destroyed are independent. The destruction of the volatile solids can produce a fixed amount of methane per unit of solids destroyed in the loading range between 0.64-3.2 kg volatile solids per cubic meter per day (0.04-0.2 lbs VS/cf-d). The total gas production increases with loading due to the fact that more carbon dioxide is produced at higher loading rates. The effects of temperature are twofold; first, higher temperature increases the activity of microorganisms, and secondly, temperature influences the solubility of gases, there is more carbon dioxide and methane released at 35°C than that at 25°C.

Figure 9 shows the effects of temperature and retention time on gas production (22). There was a rapid increase in gas production at the initial stage of digestion. After this stage, it slowed down considerably. The total gas production at the three different temperatures varied slightly. Both the total gas produced and the plateau of methane production are reached sooner at 50°C than at 30°C, and require significantly increasing times as the temperature drops to 20°C. It is of interest to note that after a certain period of digestion, there is almost no gas produced indicating the decrease in metabolic activity. At this time, most of the available organic matter has been consumed and the sludge is very stable. Thus, a large reduction in gas production rates can be an excellent indicator for measuring sludge stability or instability.

Figures 10, 11, and 12 (30) show gas production data obtained after cessation of feeding digesters raw, activated and the mixture of the two sludges. The majority of the gas production occurs in the first two to five days, depending upon the SRT, mixing regime and origin of the sludges. Gas production decreased significantly after the 5th day and reached a low rate in 12-15 days which suggests that a stable sludge was obtained. It is noteworthy that the digester fed activated sludge sustained a lower rate of gas production initially but the rate of gas production decreased more gradually with increasing digestion period.

BOD and COD of Supernatant

The BOD and COD concentrations of digester supernatant have been reported to decrease with increasing digestion retention time (40). Figure 13 shows the relationship of supernatant BOD to detention time for a mixture of primary and high-rate trickling filter sludge. The detention times selected for study were 5, 10, 20, 30, 60 and 90 days. The supernatant liquor was allowed to settle for one hour, after which the liquid portion was examined for its chemical characteristics. The BOD decreased rapidly during the first 30 days and leveled off gradually. After the 60th day, there is little BOD reduction indicating a more stable sludge was obtained. It thus appears possible to estimate the stability of a sludge by making measurements of the BOD (or COD) of the sludge liquor.

White (41) investigated the stability of various types of sludges during storage, with regard to the changes in BOD, COD, and to the effect on the

EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 237)
TYPING GUIDE SHEET

BEGIN FIRST LINE OF TEXT HERE
TYPING GUIDE SHEET
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD: BEGIN SECTIONS HERE

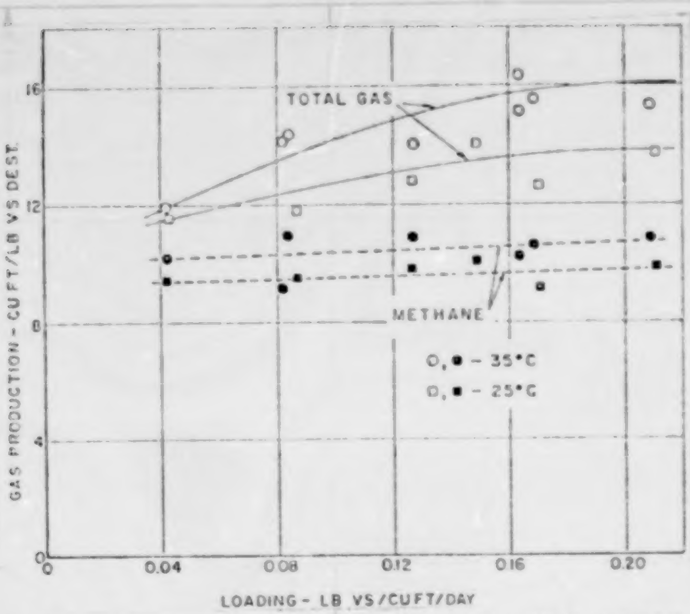


FIGURE 8 - THE EFFECT OF LOADING ON GAS PRODUCTION (39)

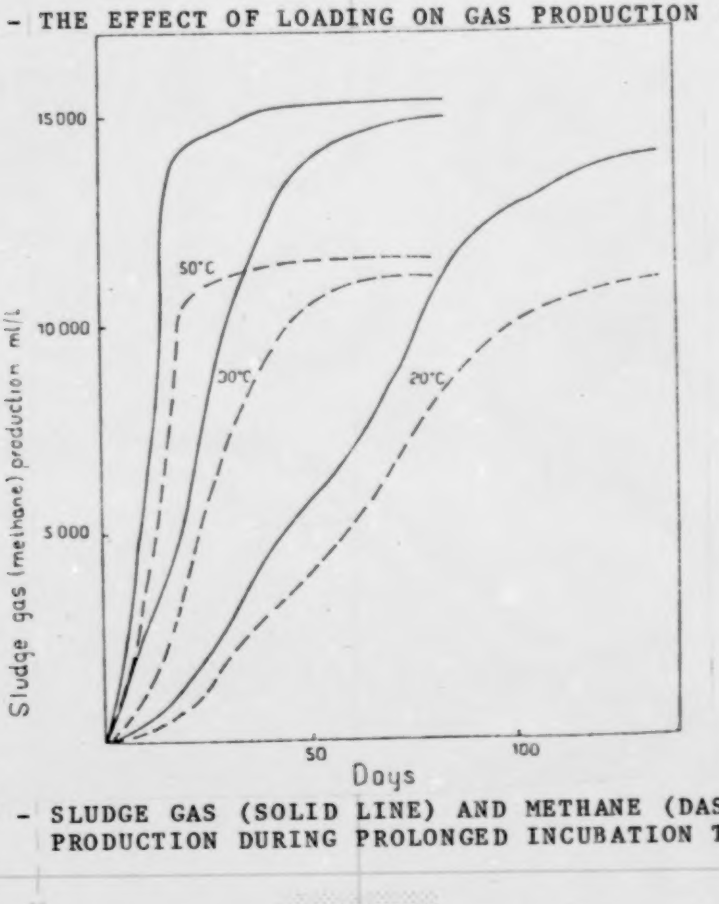


FIGURE 9 - SLUDGE GAS (SOLID LINE) AND METHANE (DASHED LINE) PRODUCTION DURING PROLONGED INCUBATION TIME (22)

BOTTOM OF IMAGE AREA, OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
BEGIN LAST LINE OF TEXT
3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

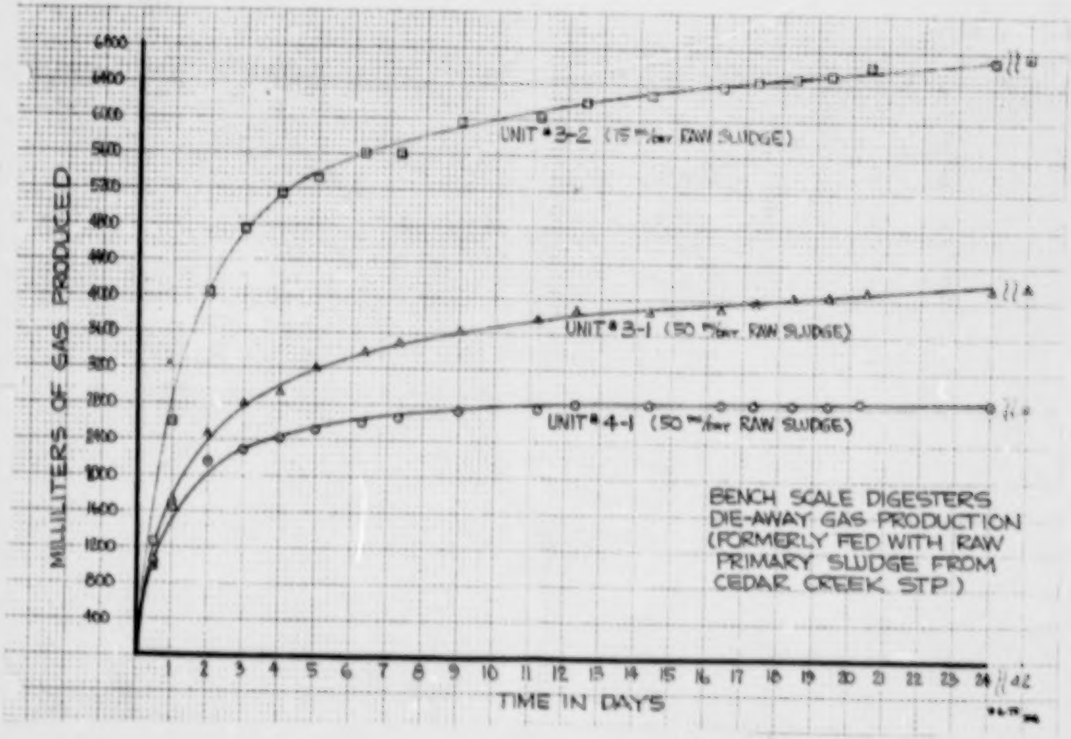


Figure 10. Bench Scale Digesters Die-Away Gas Production (Formerly Fed With Raw Primary Sludge From Cedar Creek STP).

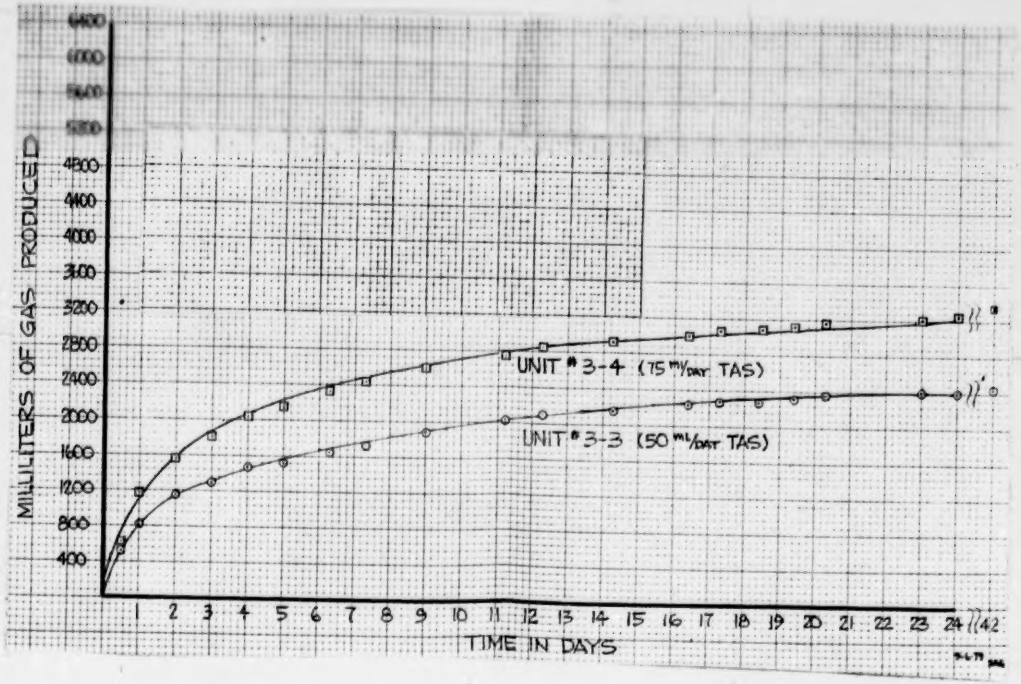


Figure 11. Bench Scale Digesters Die-Away Gas Production (Formerly Fed With Thickened Activated Sludge From Cedar Creek STP).

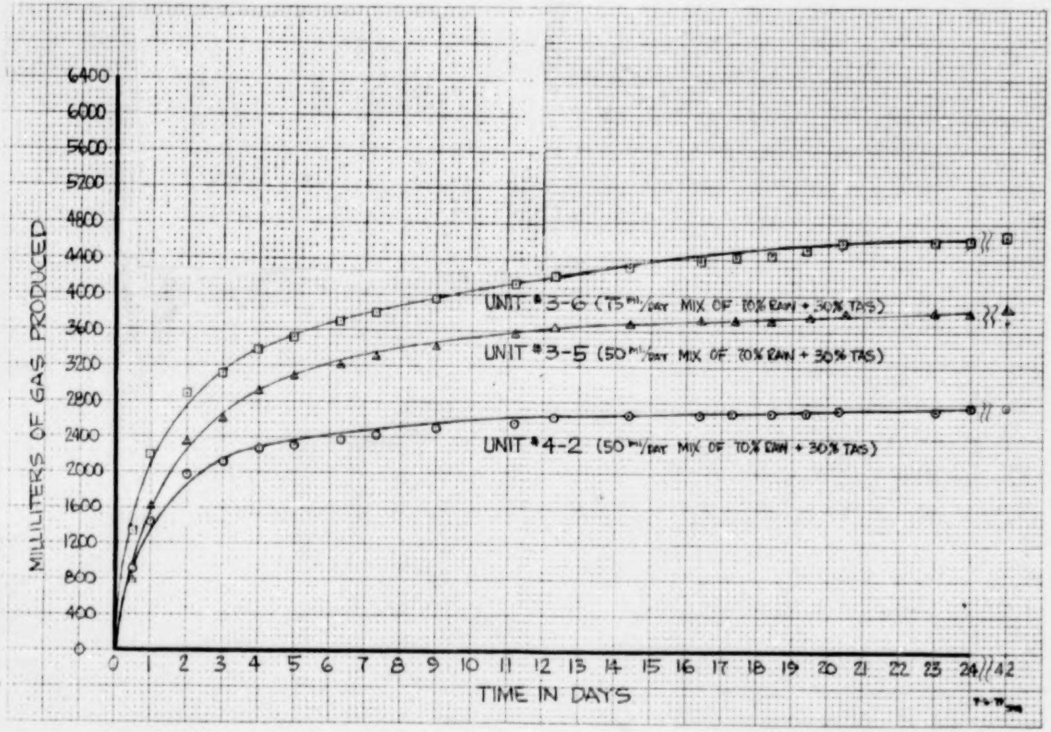


Figure 12. Bench Scale Digesters Die-Away Gas Production (Formerly Fed With 70% Raw Sludge Plus 30% Thickened Activated Sludge From Cedar Creek STP.)

EPA Form 2300-4 (4-80)
TYPING GUIDE SHEET

TYPING GUIDE SHEET
FIRST LINE OF TEXT HERE
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD: BEGIN SECTIONS HERE
8-1/8"

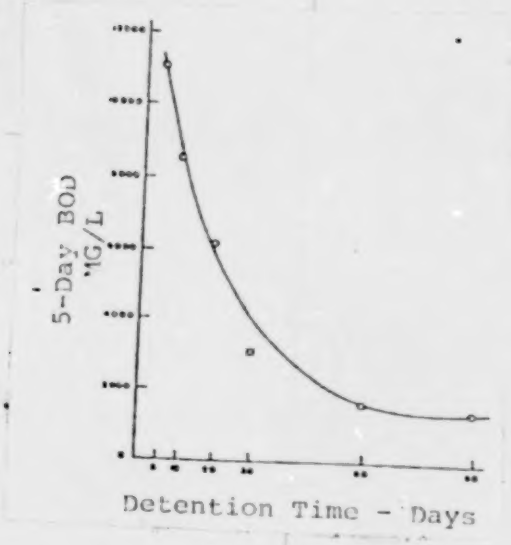


FIGURE 13 - RELATIONSHIP OF BOD OF SLUDGE SUPERNATANT TO DETENTION TIME (40)

BEGIN LAST LINE OF TEXT
BOTTOM OF IMAGE AREA: OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

filterability of the sludge. He indicated that the quality of the supernatant liquor will depend on the type of the sludge and its activity. For example, a 5-8 percent concentrated waste activated sludge with a storage time of 5 days had a concentration of BOD in the supernatant liquor of 7,300 mg/ℓ, while for a 1:5 mixture of primary and activated sludge, the concentration of BOD was reduced to 4,200 mg/ℓ. Primary, secondary, and anaerobically digested sludges were collected and stored for several days. The BOD and COD concentrations in the filtrates were measured. White indicated the rate of change of BOD or COD with storage is a good measure of stability. To compare sludges having widely different solids contents, the BOD and COD are expressed as a proportion of the concentration of dry solids. Typical results are shown in Table 11 and 12. Day zero was taken as the day of initial sampling for primary and secondary sludges. It can be seen that interstitial liquor from mixed primary sludge had high BOD and COD concentrations but showed no specific trend. With the exception of anaerobically digested sludge, all sludge interstitial liquors tended to increase in BOD and COD concentration. Tebbutt and White (42) collected a fresh primary sludge (4.4% T.S.) and measured the BOD concentration to determine its instability. The interstitial water of a fresh sample had a BOD of 2100 mg/ℓ whereas after 1 day of storage, the BOD of the filtrate increased to 3,060 mg/ℓ at 15°C and 20°C respectively. The BOD of the settled sewage was 500 mg/ℓ.

The anaerobically digested sludge, extended-aeration and low-rate activated sludges seem to be relatively stable with respect to the release of BOD and COD into the liquor. Sludges from high-rate biological treatment processes were very unstable. For example, the BOD concentration in the filtrate of a high rate biological filter sludge (humus 3.3% T.S.) at day 0 was 858 mg/ℓ, and increased to 1,949 mg/ℓ after only 2 days storage. It is noted that the data in Tables 11 and 12 were collected at 5°C. A substantially increased degree of solubilization of BOD from the solid phase would be expected at elevated temperatures. This is shown in Table 13. Both the effects of temperature and continuous mixing (one rev/min) are reported. It is clear that prolonged storage of sludge from high-rate plants should be avoided.

Table 14 shows the effect of loading on the changes in the COD of the filtrate from activated sludges during the first 24 hours storage at 20°C. Again, it can be seen that all the sludge CODs increase, and that the higher the loading on the plant, the greater the release of COD and thus the greater the degree of instability.

Odor Production

Evolution of odorous gases is one of the major problems for sludge handling and disposal. The principal odors of an organic nature arise from the anaerobic decomposition of compounds containing nitrogen and sulfur. These compounds include mercaptans, indoles, skatoles and various other nitrogen and sulfur-bearing organics (43). The most common cause and readily identifiable of the numerous odors associated with sludges is hydrogen sulfide.

Because of the large number of potential odor-causing compounds and the difficulty of measuring the strength and type of an odor quantitatively,

EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 237)
TYPING GUIDE SHEET

TABLE 11. VARIATION OF BOD IN SLUDGE LIQUOR WITH STORAGE (41)

Sludge type	Dry Solids (percent)	Weight of BOD in solution as a percentage of total DS								
		In settlement tank effluent	In interstitial liquor after storage for(days)							
			0	1	2	3	4	5	6	7
Mixed primary	3.3	0.6	3.6		3.1			3.9		
Humus (low-rate)	4.9	<0.1	0.9	1.5	2.8					6.9
Humus (high-rate)	3.3	0.3	2.6		5.3	5.8				
Activated (extended-aeration)	1.1	0.1	0.1	0.2				0.4		0.3
Activated (low-rate).....	2.2	0.1	0.1	0.4			1.0	1.1		
Activated (high-rate)....	2.0	0.1	0.1	0.5	1.3					
Anaerobically digested ..	2.5		1.1		0.2				0.1	

TABLE 12. VARIATION OF COD IN SLUDGE LIQUOR WITH STORAGE (41)

Sludge type	Dry Solids (percent)	Weight of COD in solution as a percentage of total DS									
		In settlement tank effluent	In Interstitial liquor after storage for(days)								
			0	1	2	3	4	5	6	7	9
Mixed primary	3.3	0.9	7.1	5.8	6.7			7.5			
Humus (low-rate)	4.9	0.2	1.5	2.4	3.2	4.5				10.2	
Humus (high-rate)	3.3	0.6	3.7		8.0	8.9					16.7
Activated (extended-aeration)	1.1		0.6	0.8	0.8			1.0		1.5	
Activated (low-rate) ...	2.2		0.7	1.8			2.7	2.9			
Activated (high-rate) ..	2.0		1.8	3.6						5.2	
Anaerobically digested .	2.5		2.7		1.0				0.8		

DS - Dry solids

EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 287)
TYPING GUIDE SHEET

HERE
AREA
DROPPED HEAD; BEGIN SECTIONS HERE

TABLE 13. CHANGES IN BOD OF THE FILTRATE FROM A HIGH-RATE HUMUS SLUDGE AFTER VARIOUS CONDITIONS OF STORAGE (42)
(Initial solids content of sludge, 2.1 percent

Period of storage (days)	Conditions of storage			
	10°C		20°C	
	Quiescent	Stirred	Quiescent	Stirred
	BOD of liquid phase (mg/l)			
0	700	700	700	700
1	1700	3333	1250	6000
2	1750	5170	5750	9500
3	1800	6000	6700	10000
4	2800	9750	8000	13000

9-1/8"

TABLE 14. CHANGES IN THE CHEMICAL OXYGEN DEMAND OF THE FILTRATE FROM ACTIVATED SLUDGES DURING FIRST 24 HRS' STORAGE AT 20°C (42)

Period of storage (hr)	Origin of activated sludge		
	Laboratory fill-and-draw plant (H) (extended aeration)	Sewage Works I low-rate plant	Sewage Works J high-rate plant
	COD (mg/l)		
0	44	48	160
1	42	42	205
5	46	-	230
14	38	64	265
24	62	76	550

BEGIN LAST LINE OF TEXT
BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

little research work has been done which has been associated with odor potential in sludges. However, it is one of the most important parameters related to the instability of sludge. Eikum and Paulsrud (44) have suggested a definition of sludge stability which is related to storage and has been accepted by the Commission of the European Communities. In use the "Odor Intensity Index (45) should not exceed 11 at anytime during 14 days of storage at 20°C, unless the odor can clearly be classified as a typical soil odor." The measurement of odor intensity index is tedious and laborious, and the result is somewhat subjective.

Another method measuring odor potential is the panel method (46) which involves submitting a number of people to various odors, their opinions are recorded and analyzed. This indicates an average opinion of the strength of a certain odor.

Ruffer (47) introduced the lead acetate test for measuring the degree of sludge stabilization. A number of 100 mℓ bottles with glass stoppers were filled with 50 mℓ of sludge. A strip of lead acetate paper was fastened between the bottle and the stopper. The evolution of H_2S caused the color of the lead acetate paper to change from white to brown. The time required for the color to change is a good indicator of sludge stability. It should be borne in mind that H_2S is by no means the only source that causes odor. It is probably the most important malodorous gas produced by unstable sludge. This method is simple and inexpensive to perform in both laboratory and sewage treatment plant operation.

Filterability

Filterability has been suggested as a measurement of sludge stability. The belief is that sludge dewaterability increases as stability increases. White (41) studied the filtration characteristics of various sludges with respect to their storage time and used the specific resistance results as a measure of sludge instability. On the other hand, Veslind (1) and Eikum (44) suggested that filtration properties have nothing to do with the stability of a sludge due to the inconsistent filtration results obtained by many investigators. The most common means of dewatering wastewater sludge is vacuum filtration and there are many factors that could affect the performance of the process such as the characteristics of the sludge and the operating conditions. Among the characteristics of a sludge which affect filtration are included: (48, 49, 50, 51)

(1) Solids concentration

(2) Type and nature of sludge including volatile content, size, shape and charge of the solid particles

(3) Sludge compressibility

(4) Sludge age and temperature

(5) Chemical composition

(6) Viscosity of sludge

Among the operating variables which affect filtration are:

(1) Vacuum
(2) Drum speed
(3) Filter media
(4) Conditioning of sludge prior to filtration

It is not the intent of this report to review all of these variables. However, some of the most important parameters that relate to the sludge characteristics and to the determination of sludge instability are reviewed.

Dewaterability of activated, raw and digested sludges is a characteristic of great importance to better and more economical sludge management. Studies by Karr, reported by Vesilind (1), are summarized in Table 15. These data characterize three typical wastewater sludges in terms of filterability and particle size.

TABLE 15. CHARACTERISTICS OF THREE SLUDGES: PARTICLE SIZES AND DEWATERABILITY (1)

	Type of Sludge		
	Raw Primary Sludge	Activated Sludge	Mixed Digested (Anaerobic) Sludge
Specific Resistance (m/kg)	2.1×10^4	4.8×10^3	9.3×10^{14}
CST (sec)	17	14	144
Total Solids (mg/1)	9698	8841	10,266
Rigid Settleable >100μm (percent of TS mg/ℓ)	6452	1920	3374
Fragile Settleable-settle 1 hr. (percent of TS mg/ℓ)	2320	6587	4054
Supracolloidal > 1μm (percent of TS mg/ℓ)	355	84	1997
True Colloidal >0.001μm (percent of TS mg/ℓ)	45	7	301
Dissolved (percent of TS mg/ℓ)	526	243	540

Schepman (48) studied the effect of solids concentration on filtration rate using the filter leaf test and found that the sludge filtration rates increase directly in proportion to the increase in feed sludge solids concentration (Figure 14). The slope of the curve in Figure 14 may change depending on the types of sludges used. There is, however, a practical upper limit (probably 8 to 10 percent solids for sewage sludge) which, when exceeded, makes mixing and pumping with chemicals, and sludge distribution difficult. The straight line relationship between feed solids concentration and filtration rates was confirmed by Bennett (52) and is shown in Figure 15. The

BEGIN FIRST LINE OF TEXT HERE

CENTER OF PAGE

TOP OF IMAGE AREA

DROPPED HEAD; BEGIN SECTIONS HERE

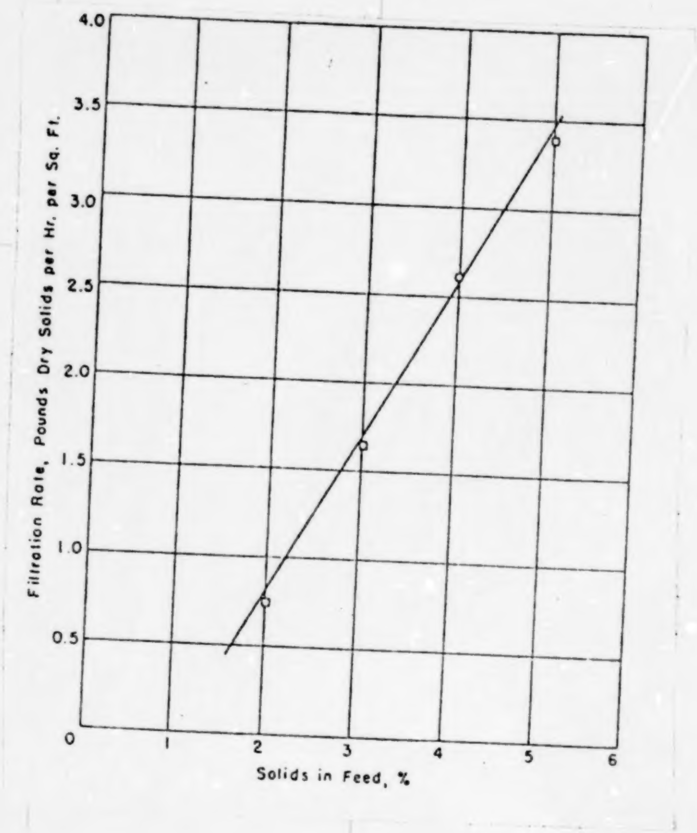


FIGURE 14. FILTRATION RATE VERSUS SOLIDS CONCENTRATION; LEAF TEST DATA FOR PRIMARY-ACTIVATED SLUDGE, EAST LANSING, MICH. MEDIUM, POLYETHYLENE 802 HF; VACUUM, 20 IN. Hg CYCLE, 3.6 MIN.; SUBMERGENCE, 25 PERCENT; CHEMICALS, 2 1/2 PERCENT $FeCl_3$ AND 10 PERCENT LIME. (48)

GIN ST LINE TEXT

3/8"

BOTTOM OF IMAGE AREA, OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS

PAGE NUMBER

EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 287)

© U.S. GOVERNMENT PRINTING OFFICE 1980-660-639

TYPING GUIDE SHEET

BEGIN FIRST LINE OF TEXT HERE
TYPING GUIDE SHEET
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD; BEGIN SECTIONS HERE

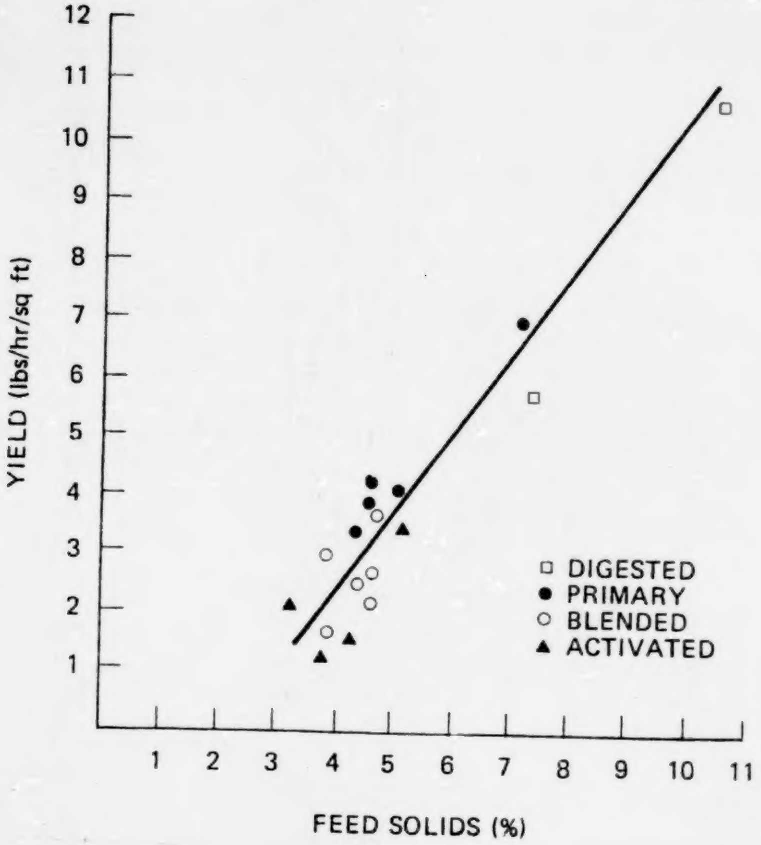


FIGURE 15 - CAKE SOLIDS AS A FUNCTION OF FEED SOLIDS FOR DIFFERENT SLUDGES (52)

BEGIN LAST LINE OF TEXT
BOTTOM OF IMAGE AREA, OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
3/8"
PAGE NUMBER
EPA-287 (Cin.)
(4-76)

sludges under study included anaerobically digested sludge, raw primary sludge, aerobically digested activated sludge, and a mixture which was made up of approximately 35 percent raw primary, 20 percent digested, and 45 percent activated sludges. It is interesting to note that the filtration rates for both primary and anaerobically digested sludges were the highest among the four and the aerobically digested activated sludge had the lowest yield, while the blended sludges gave intermediate yields. Figure 16 shows that increasing the feed solids concentration for filtration would result in the increase of cake solids concentration for various types of sludges. Again, aerobically digested activated sludge was found to form the least concentrated cake solids.

The difficulty of dewatering waste activated sludge has been concluded by many investigators (53,54,55). In a recent study conducted by Austin et al. (32) on the filterability of digested waste activated sludge, they found that a heavy dosage of chemicals was required for the anaerobically digested activated sludge in order to operate the vacuum filters without failure. The maximum cake solids concentration obtained was only 14 percent with a maximum filter yield of approximately 16.6 kg/hr-sm (3.4 lb/hr-sf). With the aerobically digested activated sludge, a cake solids concentration of 11 to 15 percent total solids was obtained while filter yields varied from 2.4 to 4.9 kg/hr-sm (0.5 to 1.0 lb/hr-sf). This is comparable to Bennett's results (Figure 17) which showed the relationship of filtration rates versus chemical cost (dosage of ferric chloride and lime) for four sludges. In general, the filter yield increased with higher chemical dose but both the aerobically digested activated and the blended sludges needed the most chemicals and gave a very low filter yield. The anaerobically digested and primary sludges showed a rapid increase of filter yield at low chemical doses. Bennett suggested that this result was due to the high fiber content of anaerobically digested and primary sludges. He indicated that the chemicals act as coagulants and agglomerate the small particles to the fiber, thus preventing blinding by the small particles at the filter medium surface and reducing the amount of dose required. Activated sludge contains very little fiber, thus sufficient chemicals must be added to cause a precipitation on each fine particle and the development of a granular matrix of larger particles. As a result, the chemical cost for conditioning of activated sludge is extremely high. Furthermore, it is difficult to filter activated sludge because it tends to form a compact mat under vacuum which leaves a small void ratio for passage of the liquid.

The performance of filtration of different sludges has been reported as varying widely. For example, Trubnick (50) studied sludges from various sources before and after digestion. In Table 16 he reported that fresh sludges are more filterable after chemical conditioning than digested sludges, and primary sludge is more filterable than secondary sludge. Burd (51) reviewed the operating records of about 60 sewage treatment plants having used ferric salts and/or lime and summarized the average date in Table 17. It is seen that, except for the digested primary sludge, the raw primary and digested sludges when blended with activated sludge are more difficult to dewater than raw sludges. It is evident that activated sludge when present in a mixture causes the deterioration in filterability. Tables 18 and 19 list some typical performance data comparing cloth and coil media rotary vacuum

EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 287)
TYPING GUIDE SHEET

BEGIN FIRST LINE OF TEXT HERE
TYPING GUIDE SHEET
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD; BEGIN SECTIONS HERE

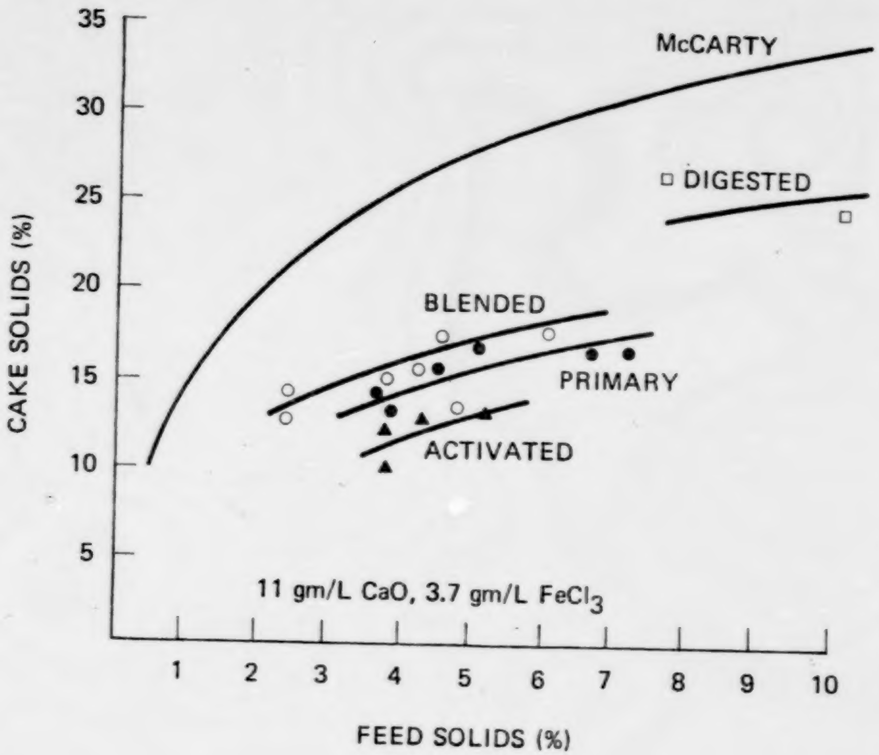


FIGURE 16 -CAKE SOLIDS AS A FUNCTION OF FEED SOLIDS FOR DIFFERENT SLUDGES. (3)

BEGIN LAST LINE OF TEXT
3/8"
BOTTOM OF IMAGE AREA OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS

EPA-287 (Cin.)
(4-76)

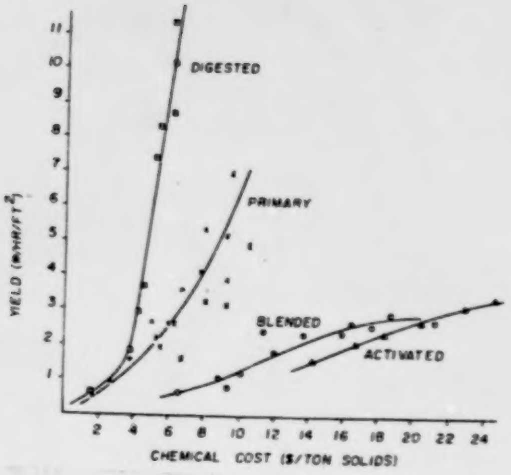


FIGURE 17. CHEMICAL COST AS A FUNCTION OF YIELD. (52)

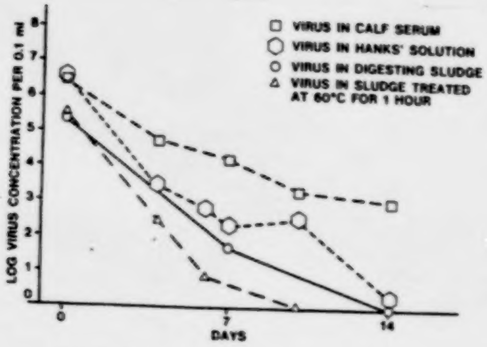


FIGURE 18. RATES OF INACTIVATION OF COXACKIEVIRUS TYPE B3 IN DIGESTER AND CONTROLS AT pH 7 AND 32°C. (59)

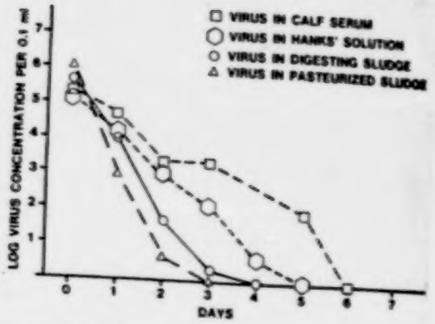


FIGURE 19. RATE OF COXACKIEVIRUS TYPE B3 IN DIGESTER AND CONTROLS AT pH 7 AND 35°C. (59)

EPA Form 2350-4 (4-80)
TYPING GUIDE SHEET

TABLE 16. MINIMUM FILTER RATES AFTER CHEMICAL CONDITIONING (50)

Type of Sludge	Filter Rate (kg/sm-hr) Fresh	Filter Rate (kg/sm-hr) Digested
Primary	3.70	34.2
Primary & trickling filter	34.2	29.3
Primary & activated	29.3	24.4
Activated or trickling filter*	14.6	-

* Thickened to at least 3 percent solids.

TABLE 17. AVERAGED VACUUM FILTRATION PERFORMANCE DATA (51)

Type of Sludge	Chemical Dose Rate (%) Ferric Chloride	Chemical Dose Rate (%) Lime	Yield (kg/sm-hr)	Cake Moisture (%)
1. Raw Primary	2.1	8.8	33.7	69.0
2. Digested primary	3.8	12.1	35.2	73.0
3. Elutriated digested primary	3.4	-0-	36.6	69.0
4. Raw primary + filter humus	2.6	11.0	34.7	75.0
5. Raw primary + activated sludge	2.6	10.1	22.0	77.5
6. Raw activated sludge	7.5	-0-	-	84.0
7. Digested primary + activated sludge	5.3	15.0	22.5	77.5
8. Digested primary + activated sludge	5.6	18.6	19.5	78.5
9. Elutriated digested primary + activated sludge:				
(a) Average w/o lime	8.4	-0-	18.6	79.0
(b) Average w/lime	2.5	6.2	18.6	76.2

HERE
OF PAGE
IMAGE AREA
DROPPED HEAD, BEGIN SECTIONS HERE
6-1/2"
9-1/8"
BEGIN LAST LINE OF TEXT
3/8"
PAGE NUMBER
BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
EPA-287 (Cin.)
(4-76)

TABLE 18. TYPICAL DEWATERING PERFORMANCE DATA FOR ROTARY VACUUM FILTERS - CLOTH MEDIA (3)

Type of sludge	Feed solids concentration, percent	Chemical dosage,[a] kg/metric dry solids		Yield,[b] kg/sm-hr	Cake, percent solids
		$FeCl_3$	CaO		
Raw primary (P)	4.5 - 9.0	20-40	80-100	1.71-39.1	27-35
Waste-activated sludge (WAS)	2.5 - 4.5	60-100	120-180	4.9-14.6	13-20
P plus WAS	3 - 7	25-40	90-120	12.2-29.3	18-25
P plus trickling filter (TF)	4 - 8	20-40	90-120	14.6-34.2	23-30
Anaerobically digested					
P	4 - 8	30-50	100-130	14.6-34.2	25-32
P plus WAS	3 - 7	40-60	150-200	9.8-24.4	18-25
P plus TF	5 - 10	40-60	125-175	17.1-39.1	20-27
Aerobically digested no primary clarification	2.5 - 6	30-70	75-120	7.3-19.5	16-23
Elutriated anaerobic digested					
P	5 - 10	25-40	0-50	19.5-39.1	27-35
P plus WAS	4.5 - 8	30-60	0-75	14.6-29.3	18-25
Thermally conditioned					
P plus WAS	6 - 15	0	0	19.5-39.1	35-45

[a] All values shown are for pure $FeCl_3$ and CaO. They must be adjusted for anything else.

[b] Filter yields depend to some extent on feed solids concentrations. Increasing the concentration normally gives a higher yield.

TABLE 19. TYPICAL DEWATERING PERFORMANCE DATA FOR ROTARY VACUUM FILTERS - COIL MEDIA (3)

Type of sludge	Feed solids concentration, percent	Chemical dosage,[a] kg/metric ton dry solids		Yield,[b]	Cake, percen solids
		$FeCl_3$	CaO	kg/sm-hr	
Raw Primary (P)	8 - 10	20-40	80-120	31.7-39.1	28-32
Trickling filter (TF)	4 - 6	20-30	50-70	29.3-39.1	20-28
P plus waste-activated sludge (WAS)	3 - 5	10-30	90-110	12.2-19.5	3-27
Anaerobically digested					
P plus TF	5 - 8	25-40	120-160	19.5-29.3	27-33
P plus WAS	4 - 6	25-40	100-150	17.1-22.0	20-25
Elutriated anaerobically digested primary	8 - 10	10-25	15-60	19.5-39.1	28-32

[a] All values shown are for pure $FeCl_3$ and CaO. This must be adjusted for anything else.

[b] Filter yields depend to some extent on feed solids concentration. Increasing the solids concentration normally gives a higher yield.

DROPPED HEAD; BEGIN SECTIONS HERE
9-1/8"
6-1/2"
BEGIN LAST LINE OF TEXT
3/8"
BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
PAGE NUMBER
EPA-287 (Cin.)
(4-76)

filters as reported in the EPA Sludge Treatment and Disposal Manual (3). It is again evident that for both the coil and cloth rotary vacuum filters the raw primary and digested primary with or without elutriation give higher filter yields than any blend which contains raw or digested activated sludge. Raw and digested trickling filter sludge also gave high yields.

Pathogenic Organisms Reductions in Anaerobic Digestion

The reduction of pathogenic organisms in sludge is especially important when the sludge is applied to land or the ocean for ultimate disposal. Anaerobic digestion reduces the number of the pathogenic organisms, but does not totally destroy them. Salmonella typhosa, Entamoeba histolitica, and Ascaris eggs can survive after 30 days of digestion (56,57). Palfi (58) has reported that digestion may reduce the virus concentration of raw sludge by 95 percent, but found several different virus types even in the digested sludge. If sludges are held in a digester for 3-8 weeks, all viruses should be destroyed (59). However, because of short-circuiting, and continuous draw-off and feed to a digester, a portion of the raw sludge does not receive sufficient residence time for complete treatment. In addition, improper design and overloading of digesters can result in high numbers of pathogenic organisms in digester effluents.

The primary pathogens that are present in sludge include viruses, bacteria, and parasites. These organisms enter waste treatment systems from a number of sources such as feces, urine of human and pet wastes, food wastes, hospital wastes, and other sources. Sludges, particularly raw primary sludge, have been known to concentrate the pathogens in sewage. Tables 20, 21, and 22 (2) list the most important viruses, bacteria and parasites together with the diseases they cause and Tables 23 and 24 give a summary of treatment effectiveness of a number of wastewater treatment processes.

Viruses

Eisenhardt (59) studied the rate of inactivation of coxackivirus B3 during anaerobic digestion and found it to be two log units in 24 hours at pH 7.0 and 35°C. Figure 18 shows that the rate of inactivation at 32°C in a high protein solution (serum) is lower than in a low protein solution (Hank's salt solution). In digesting sludge, virus is inactivated at about the same rate as in the salt solution, but pasteurized sludge appears to inactivate virus even faster than the digesting sludge. Figure 19 was obtained when all the tests were conducted at 35°C with the remaining conditions kept the same as in the previous run. It can be seen that the inactivation pattern did not change but the inactivation rate increased at the higher temperature.

Bertucci (60) seeded viruses into bench scale digestion units operating at 35°C and 14 days detention time. He reported the inactivation of Poliovirus I (Sabin), Coxsackivirus A-9, Coxsackivirus B-4, and Echovirus II was 98.8, 99.7, 99.0, and 92.5 percent, respectively, after 48 hours of digestion. He concluded that using the anaerobic digestion process inactivation of viruses follows a first-order reaction pattern. Sanders et al. (61) studied the effects of temperature and detention time of high-rate anaerobic digestion on recovery of solids-incorporated poliovirus type I (Chat). He found that at

TABLE 20. PATHOGENIC HUMAN VIRUSES POTENTIALLY IN WASTEWATER SLUDGE (3)

Name	Disease
Adenoviruses	Adenovirus infection
Coxsackie virus, Group A	Coxsackie infection; viral meningitis; AFRI[a], hand, foot, and mouth disease
Coxsackie virus, Group B	Coxsackie infection, viral meningitis; viral carditis, endemic pleuodynia, AFRI[a]
ECHO virus, (30 types)	ECHO virus infection; aseptic meningitis; AFRI[a]
Poliovirus (3 types)	Poliomyelitis
Reoviruses	Reovirus infection
Hepatitis virus A	Viral hepatitis
Norwalk agent	Sporadic viral gastroenteritis
Rotavirus	Winter vomiting disease

[a] AFRI is acute febrile respiratory illness.

DROPPED HEAD; BEGIN SECTIONS HERE

IMAGE AREA

TABLE 21. PATHOGENIC HUMAN BACTERIA POTENTIALLY IN WASTEWATER SLUDGE (3)

Species	Disease
Arizona hinshawii	Arizona infection
Bacillus cereus	*B. cereus* gastroenteritis; food poisoning
Vibrio cholerae	Cholera
Clostridium perfringens	C. perfringens gastroenteritis; food poisoning
Clostridium tetani	Tetanus
Escherichia coli	Enteropathogenic E. coli infection; acute diarrhea
Leptospira sp	Leptospirosis; Swineherd's disease
Mycobacterium tuberculosis	Tuberculosis
Salmonella paratyphi, A, B, C	Paratyphoid fever
Salmonella sendai	Paratyphoid fever
Salmonella sp. (over 1,500 serotypes)	Salmonellosis; acute diarrhea
Salmonella typhi	Typhoid fever
Shigella sp.	Shigellosis; bacillary dysentery; acute diarrhea
Yersinia enterocolitica	Yersinia gastroenteritis
Yersinia pseudotuberculosis	Mesenteric lymphadenopathy

6-1/2"

9-1/8"

BEGIN LAST LINE OF TEXT

3/8"

BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS

TEXT HERE
CENTER OF PAGE
IMAGE AREA
DROPPED HEAD; BEGIN SECTIONS HERE

TABLE 22. PATHOGENIC HUMAN AND ANIMAL PARASITES POTENTIALLY IN WASTEWATER SLUDGE (3)

Species	Disease
A. Protozoa	
Acanthamoeba sp	Ameobic meningoencephalitis
Balantidium coli	Balantidiasis, Balantidial dysentery
Dientamoeba fragilis	Dientamoeba infection
Entamoeba histolytica	Amoebiasis; amoebic dysentery
Giardia lamblia	Giardiasis
Isospora bella	Coccidiosis
Naegleria fowleri	Ameobic meningoencephalitis
Toxoplasma gordii	Toxoplasmosis
B. Nematodes	
Ancyclostoma dirodenale	Ancylostomiasis; hookworm disease
Ancyclostoma sp	Cutaneous larva migrans
Ascaris lumbricoides	Ascariasis; roundworm disease; Ascaris pneumonia
Enterobius vermicularis	Oxyuriasis; pinworm disease
Necator americanus	Necatoriasis; hookworm disease
Strongyloides stercoralis	Strongyloidiasis; hookworm disease
Toxocara canis	Dog roundworm disease, visceral larva migrans
Toxocara cati	Cat roundworm disease; visceral larva migrans
Trichusis trichiura	Trichuriasis; whipworm disease
C. Helminths	
Diphyllobothrium latum	Fish tapeworm disease
Echinococcus granulosis	Hydated disease
Echinococcus multilocularis	Aleveolar hydatid disease
Hymenolepis diminuta	Rat tapeworm disease
Tymenolepis nana	Dwarf tapeworm disease
Taenia saginata	Taeniasis; beef tapeworm disease
Taenia solium	Cysticercosis; pork tapeworm disease

BEGIN LAST LINE OF TEXT
BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLE 23. MUNICIPAL TREATMENT PLANT KILLING AND INACTIVATING PATHOGENS IN SLUDGES (64)

	Range of Effectiveness	Cost Cents/1000 gallons
1. Lime treatment (42)	a) Kills pathogenic bacteria b) At high pH (>11.5) highly effective in killing and inactivating	0.8 primary (43) 1.5 secondary
2. Heat treatment (44) - pasteurization	a) Destroys pathogens at 70°C for 1/2-1 hour	2.2-11.5 (44)
3. Composting (45)	a) Mechanical: Pathogen free after 1 day; spores 1 week	5.0-3.5 (46)
4. Anaerobic digestion (47)	a) Bacteria: Reduced at approximately natural die-off rate	1.5-0.9 (49)
	b) Helminth ova: At least 1 month for destruction	(10 MGD-50 MGD)
	c) Cysts: Destroyed in 10 days at 30°C	
	d) Virus: Some survive long periods e.g. Polio	
5. Aerobic digestion (48)	a) Reduces pathogens to low numbers.	1.8-1.0 (49) (10 MGD-50 MGD)

Note: The effectiveness and cost data are expressed as in the literature. The information is fragmentary in that the quality of the influent is not known now are variations in performance of the processes. Dates for the costs were only given for 3 (1976 $) and for 4 and 5 (1973 $).

TABLE 24. EFFECT OF SEWAGE TREATMENT PROCESSES ON INDICATOR AND PATHOGENIC MICROBIAL POPULATIONS IN RAW SEWAGE (65)

Type of Sewage Treatment	Removal Range for Various Organisms (%)
Primary	5-40
Septic Tanks	25-75
Trickling Filters	18-99
Activated Sludge	25-99
Anaerobic Digestion	25-92
Waste Stabilization Ponds	60-99
Tertiary (Flocculation, Sand Filtration, etc.)	93-99.99

34°C and 37°C the rates of inactivation were very rapid for the first 24 hours, ranging from 84 to 99 percent per day; but a slower, steady rate of 30 to 60 percent per day resulted from 24 hours until the end of the run. The secondary rates determined at different temperatures and detention times are listed in Table 25. Temperature is probably the most significant parameter on poliovirus inactivation. As shown in Figure 20, when temperature increases the rate of loss of recoverable poliovirus infectivity also increases. The data were obtained for sludge samples with a digester detention time of 10 days and a loading rate of 1.6 kg VS/m^{2}d (0.1 lb VS/cf-day). It can be seen that at 50°C, loss of infectivity reaches almost 100 percent. However, in the mesophilic range, the loss of recoverable infectivity accounted for 46 to 61 percent per day. The effect of detention time is given in Figure 21. As the temperature increases, the detention time seems to have a decreasing role in recovery. This is especially true at 50°C, where detention time has no effect on recovery because the rate of loss of recovery was so rapid. At 34°C, the effect of detention time is more significant, as shown by the lower curve. Sanders et al. (61) also compared their results with other investigations and plotted them as shown in Figure 22. It is seen that for a ten day retention time at a loading of 1.6 kg VS/m^3-d (0.1 lb VS/cf-d), four logs of viruses were lost in 10 days at 37°C and 3 logs at 34°C. It will take 30 days at 30°C to obtain four logs of virus loss according to Moore et al. (62). Sanders and her co-workers (61) claimed this difference was probably caused by the method of adding the virus, the digester operation, or sample preparation. These parameters are listed in Table 26.

TABLE 25. RATE OF LOSS OF RECOVERABLE POLIOVIRUS INFECTIVITY AT 1.6 kVS/m^3 - d (61)

Temperature (°C)	Sample	Rate (%/d)	r^2
34	Control	22	0.97
	5-day detention	37	0.88
	10-day detention	48	0.96
37	Control	34	0.86
	5-day detention	59	1.00
	10-day detention	56	0.98
	15-day detention	61	0.99
50	Control	99.999998	0.97
	5-day detention	99.999998	1.00
	10-day detention	99.999998	1.00

Parasites

Potential parasitic disease agents in sludge are protozoan and metazoan parasites having a stage in man which releases infective cysts or eggs into feces or urine, or animal parasite eggs and cysts entering sewage via slaughterhouse wastewater or street drainage. Some of the parasitic eggs and

EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 337)
TYPING GUIDE SHEET

BEGIN FIRST LINE OF TEXT HERE
TYPING GUIDE SHEET
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD; BEGIN SECTIONS HERE
9-1/8"

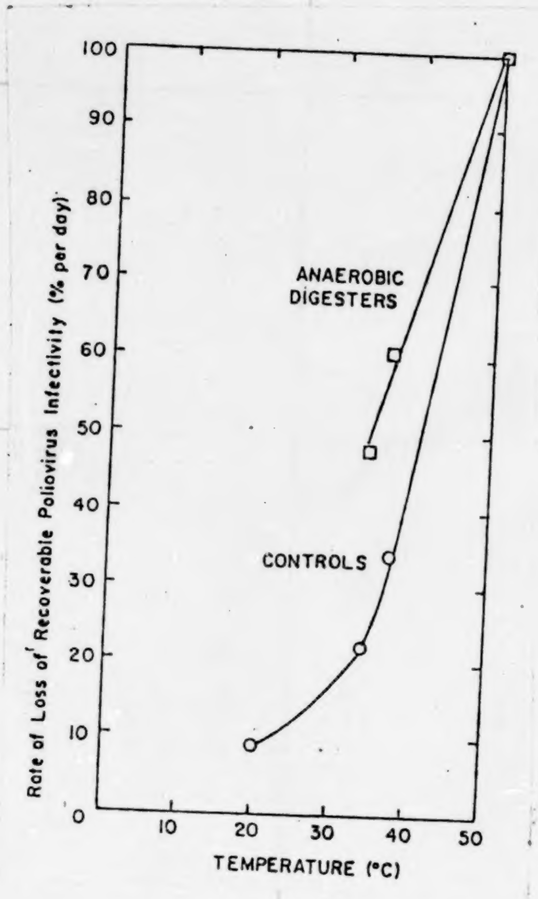


FIGURE 20 - EFFECT OF TEMPERATURE ON RATE OF LOSS OF RECOVERABLE POLIOVIRUS INFECTIVITY. (61)

BEGIN LAST LINE OF TEXT
3/8"
BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS

EPA-287 (Cin.)
(4-76)

BEGIN FIRST LINE OF TEXT HERE
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD; BEGIN SECTIONS HERE
9-1/8"

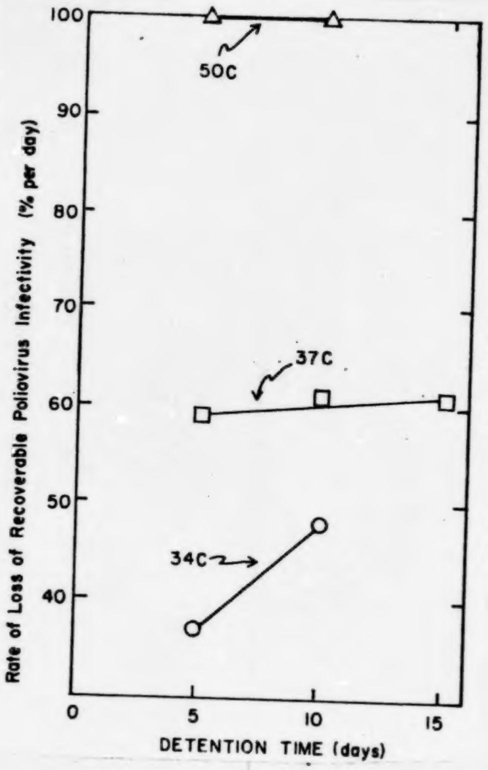


FIGURE 21. EFFECT OF DETENTION TIME ON RATE OF LOSS OF RECOVERABLE POLIOVIRUS INFECTIVITY. (61)

BEGIN LAST LINE OF TEXT
3/8"
BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS

PAGE NUMBER
EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN: EPA FORM 28Y)
U.S. GOVERNMENT PRINTING OFFICE: 1980-660-639
TYPING GUIDE SHEET

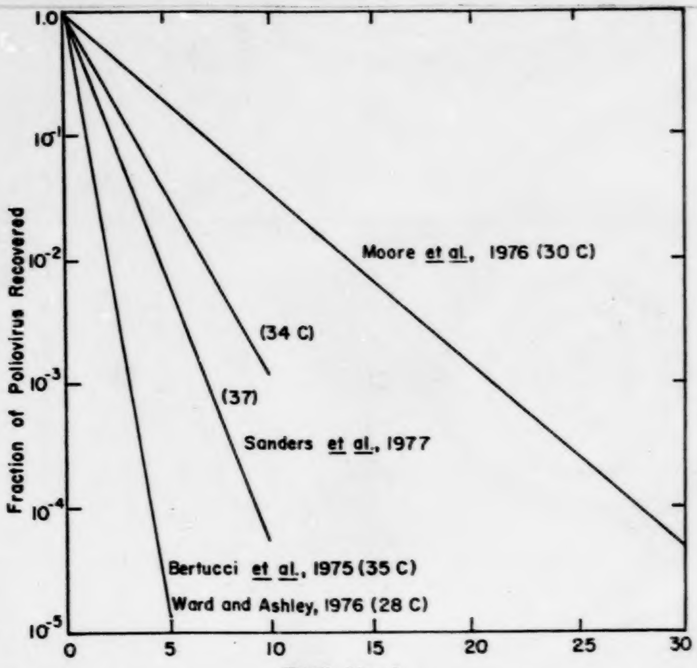


FIGURE 22. POLIOVIRUS RECOVERY DURING ANAEROBIC SLUDGE DIGESTION. (61)

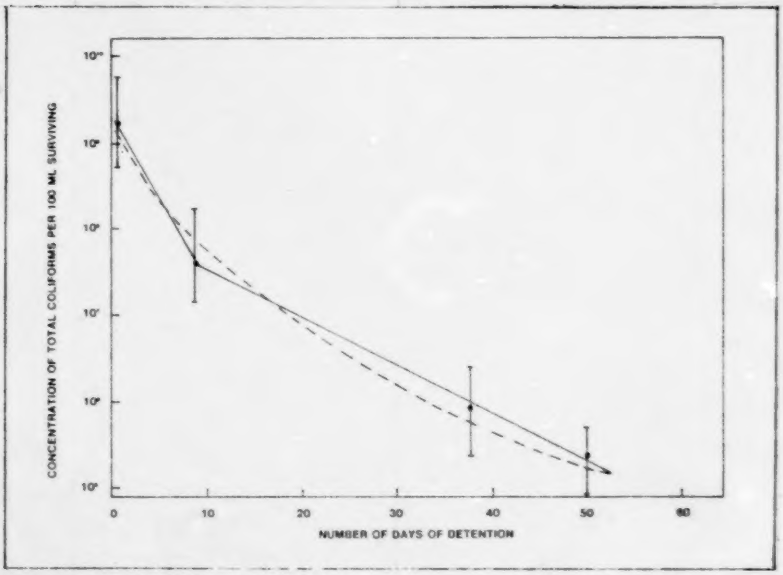


Figure 3. Concentration of Coliforms Surviving as a Function of Detention Time.

FIGURE 23. CONCENTRATION OF COLIFORMS SURVIVING AS A FUNCTION OF DETENTION TIME. (74)

BEGIN FIRST LINE OF TEXT HERE
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD: BEGIN SECTIONS HERE
BEGIN LAST LINE OF TEXT
3/8"
PAGE NUMBER
BOTTOM OF IMAGE AREA OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 287)
TYPING GUIDE SHEET

TABLE 26. COMPARISON OF METHODS AND EXPERIMENTAL CONDITIONS FOR RECENT STUDIES ON VIRUS RECOVERY DURING ANAEROBIC DIGESTION (61,62)

Parameter	Present Study Conditions	Other Recent Studies Moore et al.(62)	 Bertucci et al.(60)	 Ward and Ashley(63)
Type digester	Continuous (fill & draw)	Batch	Continuous (fill & draw)	Batch
Theoretical detention time	5,10,15 days	N/A	14 days	N/A
Mixing	Continuous	None	continuous	Initial 15 min. only
Temperature, °C	34,37,50	30	35	28
Virus	Poliovirus 1 (Chat)	Poliovirus 1 (Chat)	Poliovirus 1 (Sabin)	Poliovirus 1 (Chat)
Virus addition	Incorporation into MLSS	Incorporation into MLSS	Mixed with sludge	Mixed with sludge
Preparation for assay	Direct plate	Homogenized with tryptose phosphate broth, separated, eluate assayed	Dilution (10x) in 5% FCS 3% BE; 1% gelatine; sonication for 20 minutes; direct assay	Sonication for 2 minutes with sodium dodecyl sulfate in PBS at various dilutions; direct assay or separated
pH	6.0 to 7.2	7.0 to 7.5	7.2 to 7.4	-

LINE OF TEXT HERE
DROPPED HEAD: BEGIN SECTIONS HERE
OF PAGE
IMAGE AREA
BEGIN LAST LINE OF TEXT
3/8"
BOTTOM OF IMAGE AREA, OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
PAGE NUMBER

cysts have resistant stages that are likely to pass through a sewage plant in a viable state. Recent research (66) has shown that the only processes which have been found to remove or destroy resistant stages are dependent upon the mechanisms of filtration or settling. The weight of an egg or cyst determines its settleability. For example, helminth eggs, particularly Ascaris eggs are heavier and therefore settle out rather rapidly. Protozoan cysts are lighter; they are more frequently found in the liquid effluent. Liebmann (67) reported that a 2 hour sedimentation period was sufficient to remove all eggs with a specific gravity of 1.1 or greater. It was reported that 68 percent of the eggs of Taenia saginata were settled in raw sewage after 2 hours, and 89 percent in 3 hours.

In general, secondary treatment processes including the trickling filter and activated sludge processes are ineffective in destroying parasites (66, 68, 69). All reports on the effect of the trickling filter or activated sludge process confirm that the eggs will eventually accumulate in the sludge, with some lighter eggs and cysts remaining suspended in the effluent liquid.

The fate of cysts and eggs during anaerobic digestion is important. The efficiency of destroying parasitic cysts and eggs is dependent upon the operating temperature and detention time. Hays (68) summarized the available research on the survival of parasitic eggs or cysts during anaerobic digestion at various temperatures and detention times (Table 27). He indicated that anaerobic digestion can destroy all protozoan cysts but was less effective on eggs. Operating temperatures in the thermophilic range (> 45°C) are helpful in destroying eggs. Since most anaerobic digesters were operated in the mesophilic range with continuous feed and draw-off, it was difficult to obtain 100 percent removal efficiency.

Bacteria

Tables 28 and 29 (1, 3) list some typical concentrations of pathogenic bacteria in various sludges. The results vary widely depending on the source and type of sludge, the sensitivity of assay techniques, and the operating conditions of the digesters. Ruchhoft (70) found 25 to 75 percent removal of Salmonella typhosa depending on retention time while McKinney et al. (71) reported 84 and 92.4 percent reductions after 6 and 20 days, respectively. Mom et al. (72) were unable to detect the presence of viable S. typhosa after 6 to 8 days. It was observed by two groups (73) that there was 90 and 69 percent removal of Mycobacterium tuberculosis, while others (73) noted "survival" of M. tuberculosis after anaerobic digestion. In general, anaerobic digestion reduces bacterial counts by one to four orders of magnitude (3,74). Increasing both temperature and detention time also increases the reduction rate. Figures 23 and 24 show the effect of anaerobic detention time on the survival of coliforms and salmonellae (74).

TABLE 27. SURVIVAL IN ANAEROBIC DIGESTERS (68)

Organism	Time in digester	Temperature of digester (°C)	Survival of eggs or cyst (%)
Ascaris lumbricoides			
Cram 1943	6 months	20°C	10
Reyes et al., 1963	30 days	38	0
	20 days	45	0
	20 min	55-60	0
Hookworm			
Cram 1943	64 days	20	some survival
	41 days	30	some survival
	36 days	room temp.	some survival
Taenia saginata			
Newton et al., 1949	6 months	24-30	some survival
Vasskova, 1966 (from Kabler 1959)			3%
Schistosoma japonicum			
Newton et al., 1948	21 days	15-24	0
Jones 1947	9 days	20-32	0
(from Kabler 1959)	25-35 days		10%
Mijares 1964	more than 21 days	30	0
Entamoeba histolytica			
Cram 1943	>12 days	20	0
	>10 days	30	0
	>4 days	-12 to 19°C	0

EPA-287 (Cin.)
(4-76)

TABLE 28. PATHOGENIC BACTERIA IN SLUDGE (1)

Sludge	Coliform (10^6/mℓ)	Salmonella (per 100 mℓ)	Pseudomonas (per 100 mℓ)
Raw Primary	11.0-11.4	460	46,000
Activated	2-2.8	74-23,000	1,100-24,000
Trickling Filter	11.5	93	11,000
Mixed Digested	0.4	29	34
Source	Farrell (1974)	Farrell (1974)	Farrell (1974)

TABLE 29. PATHOGEN OCCURRENCE IN LIQUID WASTEWATER SLUDGES (3)

Pathogen	Name or species	Concentration, number/100 ml Unstabilized raw sludge[a]	 Digested sludge[a,b]
Bacteria	*Clostridia* sp	6×10^6	2×10^7
Bacteria	Fecal coliform	10^9	$3 \times 10^4 - 6 \times 10^6$
Bacteria	*Salmonella sp.*	8×10^3	BDL[c]- 62
Bacteria	*Streptococcus faecalis*	3×10^7	$4 \times 10^4 - 2 \times 10^6$
Bacteria	Total coliforms	5×10^9	$6 \times 10^4 - 7 \times 10^7$
Bacteria	*Mycobacterium tuberculosis*	10^7	10^6

[a] Type of sludge usually unspecified.

[b] Anaerobic digestion; temperature and detention times varied.

[c] BDL is below detection limits, <3/100 ml.

HERE
OF PAGE
IMAGE AREA
DROPPED HEAD BEGIN SECTIONS HERE
BEGIN LAST LINE OF TEXT
3/8"
PAGE NUMBER
BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
EPA-287 (Cin.)
(4-76)

BEGIN FIRST LINE OF TEXT HERE
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD; BEGIN SECTIONS HERE

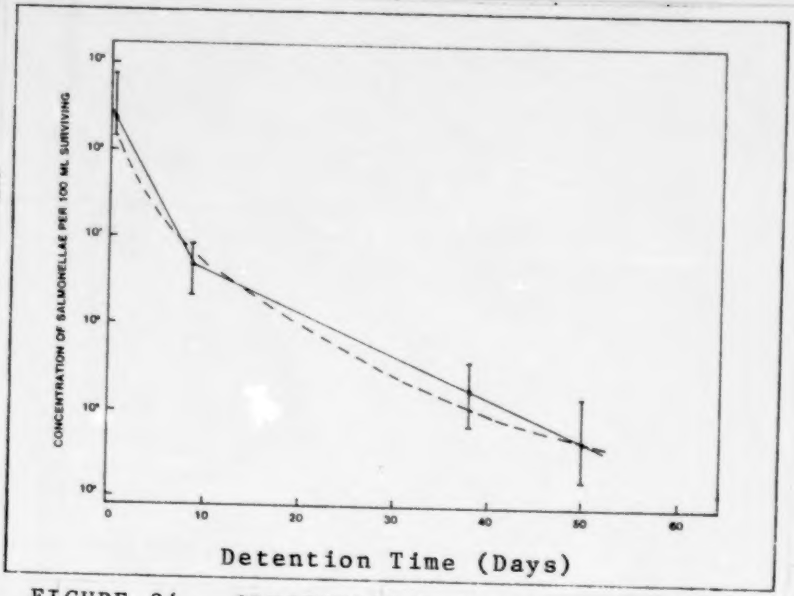


FIGURE 24. CONCENTRATION OF SALMONELLAE SURVIVING AS A FUNCTION OF DETENTION TIME. (74)

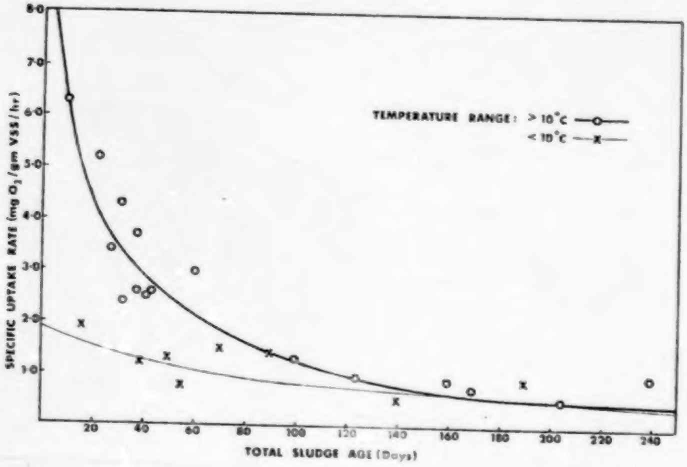


FIGURE 25. OXYGEN UTILIZATION RATES. (75)

BEGIN LAST LINE OF TEXT
BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS

PAGE NUMBER
EPA Form 2350-4 (4-80)
(PREVIOUSLY C.N. EPA FORM 287)
☆ U.S. GOVERNMENT PRINTING OFFICE: 1980-650-026
TYPING GUIDE SHEET

AEROBICALLY DIGESTED SLUDGE

Aerobic digestion is a process designed to stabilize sludges from aerobic secondary processes by conversion of the degradable portion of sludges into carbon dioxide and water through microbial metabolism and extended periods of aeration. When there is inadequate external substrate available, microorganisms can consume their own cellular mass for metabolism, and this is referred to as "endogenous respiration". The ideal product is a stable, non-odorous sludge.

Parameters of instability include specific oxygen uptake rate, odor production, volatile solids reduction, nitrification, and adenosine triphosphate concentration. The following sections review these parameters.

Specific Oxygen Uptake Rate

In aerobic digesters, microorganisms consume oxygen while degrading the substrate. The specific oxygen uptake rate (SOUR) is a reliable index measuring the activity of the cells or the instability of sludge. A high SOUR would indicate a very active, viable sludge, while a low SOUR indicates a more stable sludge which has reached a state of respiration where its biological action is minimal.

Important factors that affect the SOUR are: type and history of sludge, temperature, sludge age, and digester operating conditions. For example, primary sludge has a high SOUR and tends to promote sludge synthesis. Depending on the loading rate waste activated sludge may have a high to low SOUR. Extended aeration studies may be in a state of endogenous respiration. Specific uptake rates of primary sludges in excess of 40 mg O_2/g VSS-hr have been measured. Typical SOUR values for conventional activated sludge, extended aeration sludge, and aerobically digested sludge are in the range of 10-15, 5-8, and 0.5-4 mg O_2/g VSS-hr, respectively. Figure 22 shows the effect of sludge age and temperature on the specific uptake rate. Data were obtained from a number of sewage treatment plants and the total sludge age was defined as age in the digester plus the age when wasted to the digester (75). It is seen that the specific uptake rate decreases with increasing sludge age and decreasing digestion temperature. The biological activity approaches a minimum after a total sludge age of 120 days. Sludge has probably reached its most stable stage at this point. Thus, Ahlberg et al. (75) suggested that under normal conditions, a specific uptake rate of less than one usually indicates a stable sludge. Loers et al. (76) studied the uptake rate for aerobically digested activated sludge at a low temperature and confirmed Ahlberg's suggestion for sludge digested at 20°C, but not at 10°C and 5°C. Figure 26 shows the effects of temperature and sludge age on oxygen uptake rates for raw and digested waste activated sludge. A sludge with a SOUR value of 1 mg/g VSS-hr at 5°C would have a higher SOUR value than when subjected to temperatures of 10°C or 20°C. Thus, at low temperatures, SOUR must be adjusted for measuring sludge instability. It is noted that the digester sludge age was defined as the weight of VSS in the digester divided by the weight of VSS wasted from the digester each day.

Hartman (77) compared the SOUR measured during the batch digestion period at high temperatures and plotted the results in Fig. 27. The sludge

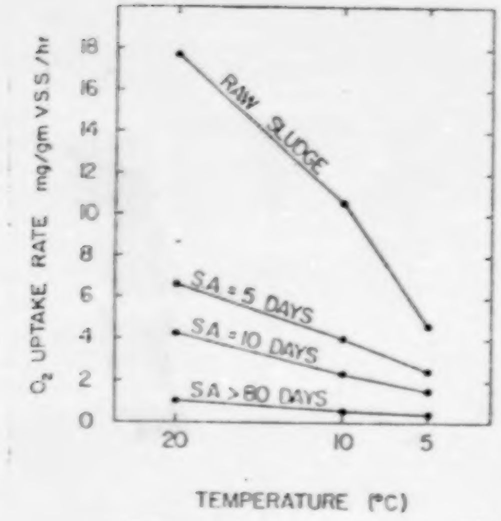


FIGURE 26. OXYGEN UPTAKE RATE VERSUS TEMPERATURE. (76)

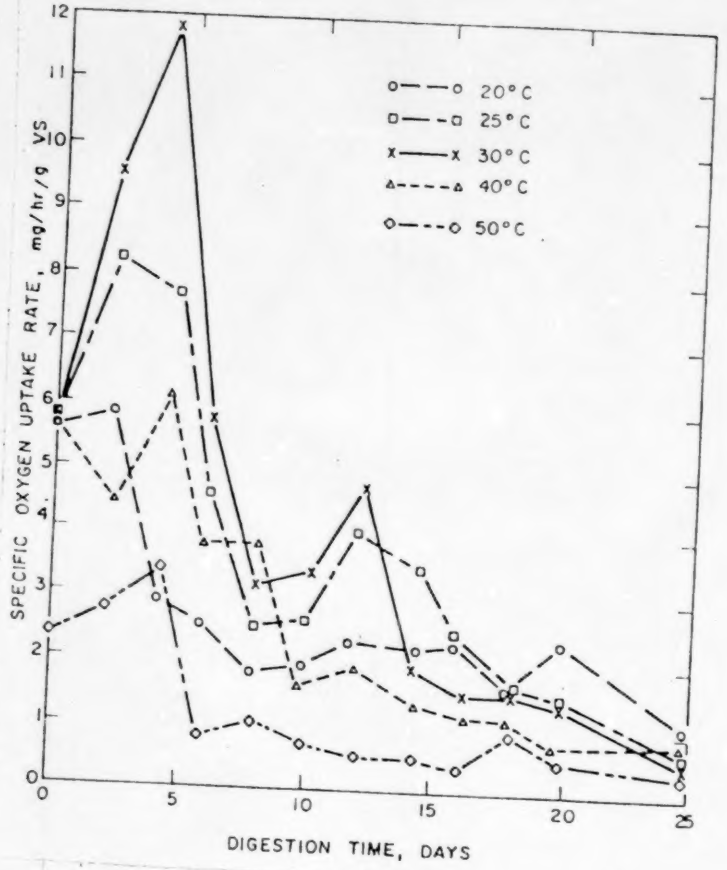


FIGURE 27. SPECIFIC OXYGEN UPTAKE RATES AT VARIOUS OPERATING TEMPERATURES, BATCH DIGESTION OF A 26% TOTAL VOLATILE SOLIDS SLUDGE. (77)

BEGIN FIRST LINE OF TEXT HERE
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD: BEGIN SECTIONS HERE
BEGIN LAST LINE OF TEXT
3/8"
BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
PAGE NUMBER
EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 287)
☆ U.S. GOVERNMENT PRINTING OFFICE: 1980-660-639
TYPING GUIDE SHEET

under study was mixed primary and trickling filter humus. There was a significant increase in rate at all temperatures during the initial phase of aerobic digestion. This was interpreted as the increase in the active biomass utilizing the substrate available in the primary sludge fraction of the feed material. This initial increase was followed by a rapid decline and levelling-off phases which were related to a corresponding decrease in the active mass during the remaining digestion period.

Eikum and Paulsrud (44) studied oxygen uptake rates for various types of sludges during aerobic digestion at 18°C. The results are shown in Figure 28. Again, the oxygen uptake rate increases at the initial stage of digestion, but is followed by a gradual decrease. They defined a fully aerobic stabilized sludge as having an odor intensity index below 11 during 14 days of storage at 20°C. The required retention time to obtain this stable sludge can be obtained from Figure 29 where the curve levels off. The sludge stability can be correlated to SOUR by equation (1):

$$S = 100A\left(1 - \frac{\text{OUR meas.}}{\text{OUR max.}}\right) \qquad (1)$$

S = sludge stability (%)

A = constant

OUR meas. = oxygen uptake rate measured and adjusted to 18°C

OUR max. = maximum oxygen uptake rate during batch stabilization at 18°C

Equation (2) was used for temperature adjustment.

$$\frac{OUR_{T_1}}{OUR_{T_2}} = \theta^{(T_1 - T_2)} \qquad (2)$$

OUR_{T_1} = oxygen uptake rate at temperature T_1

OUR_{T_2} = oxygen uptake rate at temperature T_2

θ = The Streeter-Phelps temperature sensitivity coefficient

A family of curves was developed (Figure 30) showing the relationship between temperature, oxygen uptake rate and sludge stability.

Odor Production

Eikum (78) used Ruffer's lead-acetate test measuring the stability of primary and aerobically digested primary sludges. The evolution of hydrogen sulfide gas can cause paper impregnated with lead acetate to change color from white to brown to black. The time required for a color change to occur using different sludges subjected to various degrees of treatment was used as a measure of sludge stability. Table 30 shows some typical results obtained by Eikum. It took only 10 minutes for raw primary sludge to change

BEGIN FIRST LINE OF TEXT HERE
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD BEGIN SECTIONS HERE
6-1/2"
9-1/8"

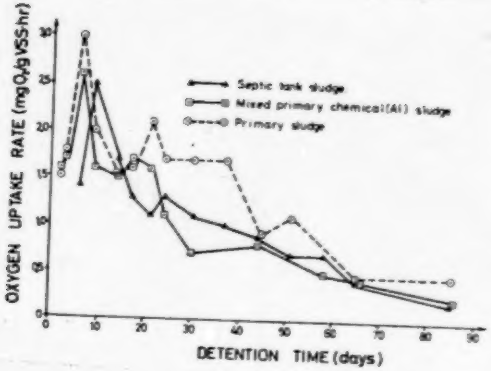


FIGURE 28. OXYGEN UPTAKE RATE VS. DETENTION TIME IN AEROBIC DIGESTER. (44)

BEGIN LAST LINE OF TEXT
3/8"

PAGE NUMBER
BOTTOM OF IMAGE AREA OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 287)
☆ U.S. GOVERNMENT PRINTING OFFICE
TYPING GUIDE SHEET

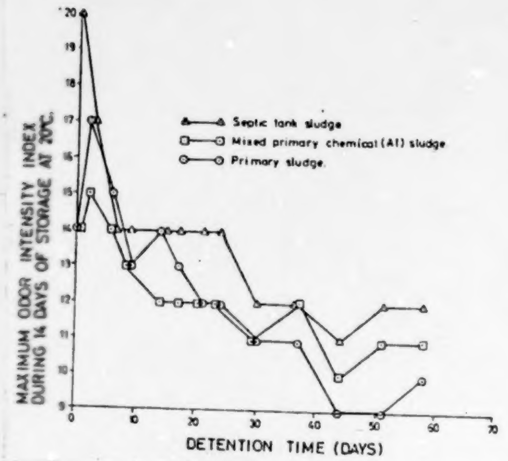


FIGURE 29. MAXIMUM ODOUR INTENSITY INDEX MEASURED DURING 14 DAYS OF STORAGE VS. DETENTION TIME IN AEROBIC DIGESTER. (44)

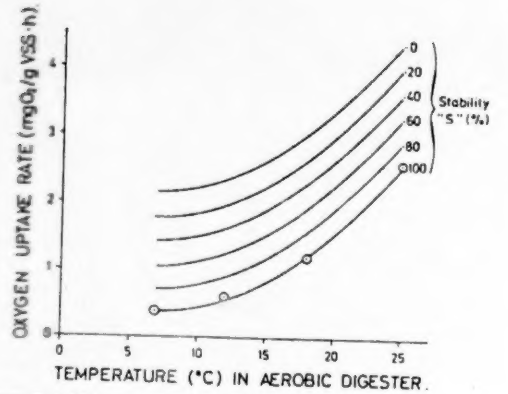


FIGURE 30. OXYGEN UPTAKE RATE AND DEGREE OF STABILITY (%) VS. TEMPERATURE IN AEROBIC STABILIZATION UNIT, PRIMARY SLUDGE. (44)

EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 267)
☆ U.S. GOVERNMENT PRINTING OFFICE 1980-660-639
TYPING GUIDE SHEET

TABLE 30. LEAD ACETATE TEST - PRIMARY SLUDGE (78)

UNIT	Prim.	A1	A2	A3	A4	A5
Detention Time (days)	0	5	10	15	25	35
Temp. °C	-	18	18	18	18	18
Days Before Color Appears	10 min	4	4	NC	NC	NC

NC indicates no color in 20 days

the color of the paper, indicating a very unstable sludge which produced a large amount of H_2O gas and an offensive odor. For aerobically digested sludge with 5 and 10 days detention time, 4 days were required to color the strip, indicating the greater stability of the sludge. When the detention time exceeded 10 days, H_2S evolution during the 20 days of testing was not detected.

Hartman et al. (79) modified the lead acetate paper procedure by placing 10 ml of sludge sample in a six inch test tube and incubating at 37°C. The temperature of 37°C was chosen because it was claimed that temperatures in the range of 30 to 50°C are optimum for the growth of *Desulfovibrio*, the species that produces H_2S. Typical results are shown in Figure 31. It is seen in the lower curve that the stability index (i.e., days to produce a color change in the paper strip) is low and is constant initially indicating instability but then increases rapidly as a more stable sludge is produced. Both the volatile solids reduction and SOUR curves show little change with increased digestion time at this stage indicating that they may not be as sensitive an indicator of sludge instability.

Figures 32 and 33 show the effects of temperature and volatile solids concentration on sludge stability index. The mixture of primary and trickling filter humus was digested aerobically at 20, 30, 40, and 50°C. The stability index was plotted with digestion time. The sludge digested at 30°C (Figure 33), the required digestion period for a desired product stability increased as the initial volatile solids concentration of the feed sludge increased.

The stability index was also plotted against the specific oxygen uptake rate shown in Figure 34 for comparison. For an active biological sludge with a high SOUR value, the stability index is very small. However, as the SOUR decreased, the stability index increased slowly. When the uptake rate dropped below 2 mg/g VSS-hr, the stability exhibited a dramatic increase.

It should be borne in mind that there are many other compounds contribu-

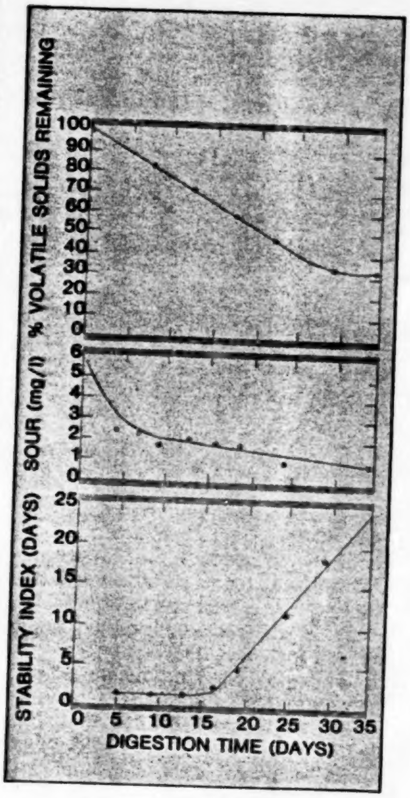


FIGURE 31. VARIATION OF PERFORMANCE PARAMETERS WITH TIME FOR PRIMARY SLUDGE/TRICKLING FILTER HUMUS DIGESTED AT 20°C. (79)

EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 287)
© U.S. GOVERNMENT PRINTING OFFICE 1980-660-839
TYPING GUIDE SHEET

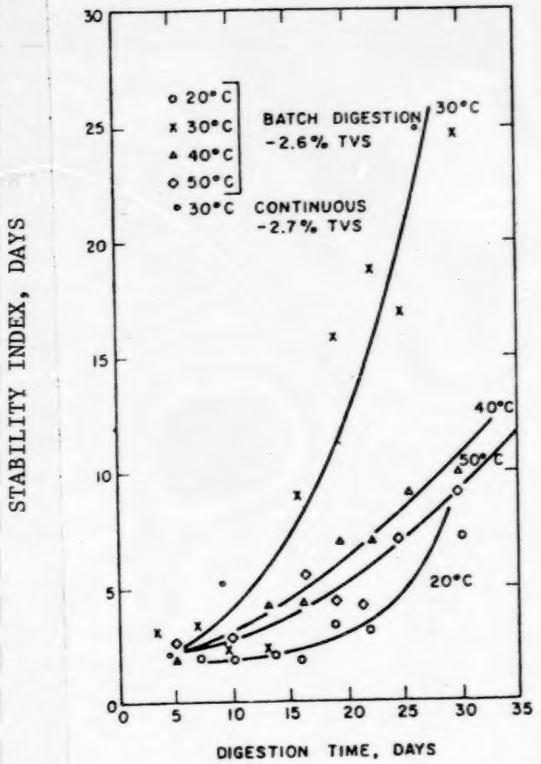


FIGURE 32. UNDRAINED STABILITY INDEX FOR VARIOUS OPERATING TEMPERATURES. (77)

EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 2s7)
TYPING GUIDE SHEET

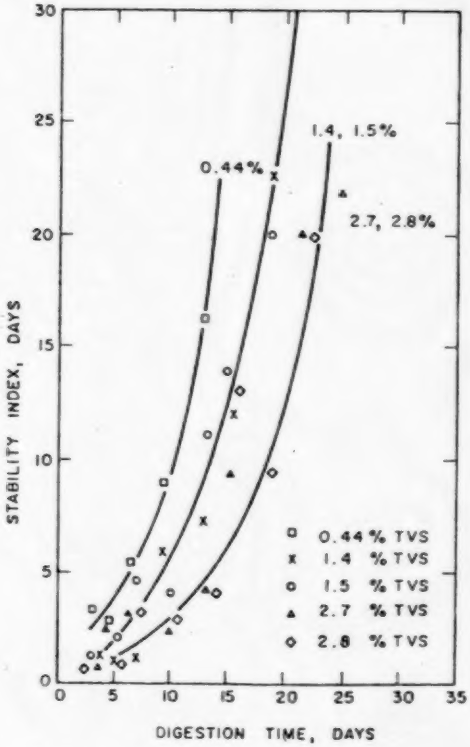


FIGURE 33 - UNDRAINED STABILITY INDEX FOR VARIOUS FEED SLUDGE CONCENTRATIONS. BATCH DIGESTION AT 30°C. (77)

BEGIN FIRST LINE OF TEXT HERE
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD: BEGIN SECTIONS HERE

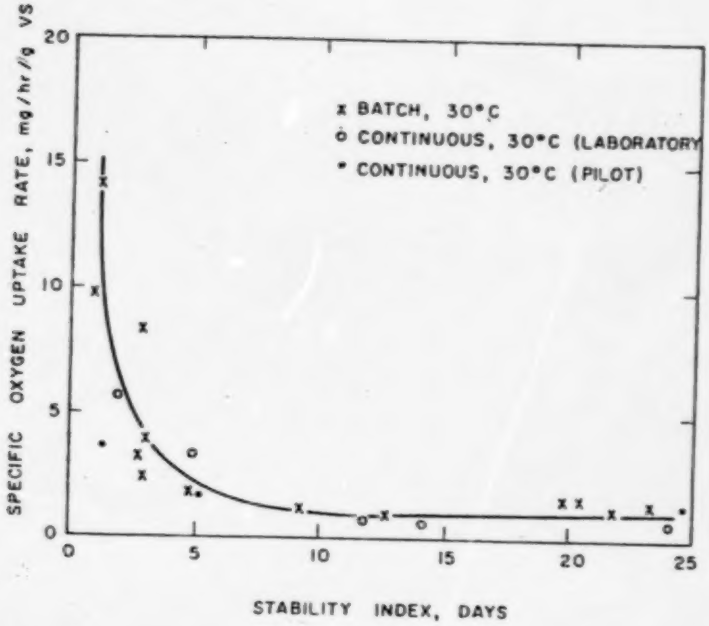


FIGURE 34. COMPARISON OF SPECIFIC OXYGEN UPTAKE RATE AND UNDRAINED STABILITY INDEX FOR DIGESTION AT 30°C. (77)

BEGIN LAST LINE OF TEXT
BOTTOM OF IMAGE AREA OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS

PAGE NUMBER
EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 337)
TYPING GUIDE SHEET

ting odor problems in addition to H_2S gas. The lead acetate paper test presents a simple and practical method measuring the evolution of H_2S. The basic premise of the lead acetate test is that H_2S is the predominant gas producing odor in sludge, and can be used as a measure of sludge instability.

Volatile Solids Reduction

In aerobic digestion, the volatile solids concentration decreases with increasing detention time. After some time, the percent volatile solids reaches a constant value. Many investigators suggested that constant volatile solids concentration indicates a stable sludge. However, some disagreed (1,44,77,78), because small variations in the percent reduction of volatile matter may reflect large changes in the stability. When sufficient data is available, it may be possible to correlate volatile solids reduction rate with SOUR, odor production potential, and other parameters to measure sludge stability.

Reduction of volatile solids as a function of detention time and sludge age are given in Figures 35 and 36 respectively (80,81). In general, most of the volatile solid destruction will occur during the first 10 to 15 days of aeration detention time.

The change in biodegradable volatile solids can be represented by the following first order model:

$$\frac{dx_d}{dt} = -K_d x_d \tag{3}$$

where:

$\frac{dx_d}{dt}$ = rate of change of biodegradable volatile solids concentration

K_d = decay rate (day^{-1})

x_d = biodegradable volatile solids concentration ($\frac{mg}{\ell}$)

t = time (day)

Equation (3) can be integrated to yield:

$$\frac{x_d}{x_d^\circ} = e^{-K_d t} \tag{4}$$

where:

x_d° = initial biodegradable volatile solids concentration ($\frac{mg}{\ell}$)

EPA-287 (Cin.) (4-78)

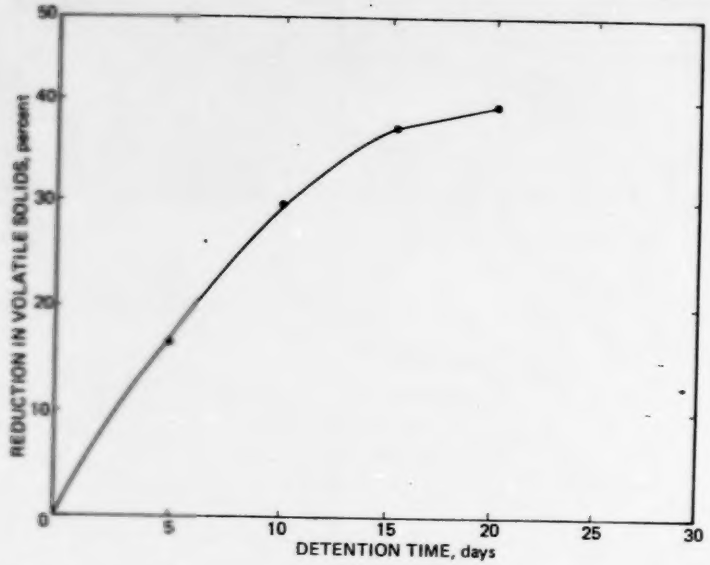


FIGURE 35. EFFECT OF DETENTION TIME ON AEROBIC DIGESTION OF ACTIVATED SLUDGE. (80)

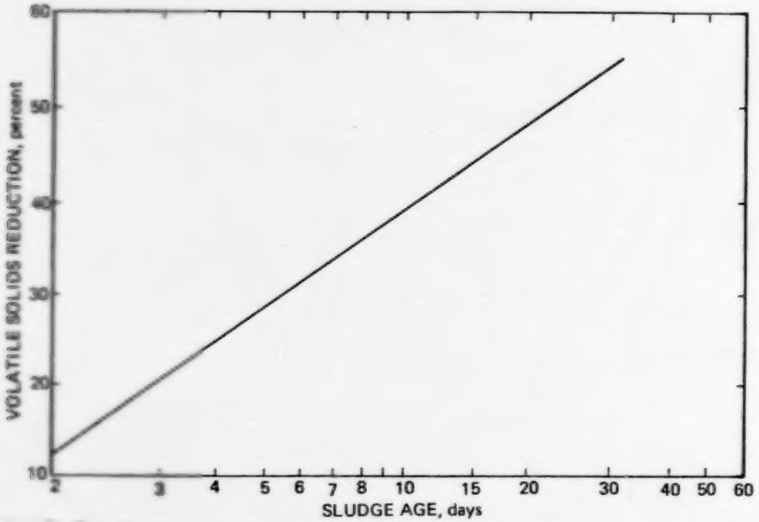


FIGURE 36. VOLATILE SOLIDS REDUCTIONS AS A FUNCTION OF SLUDGE AGE. (81)

Equation (4) will yield a straight line when plotted on semilog paper. Values of $\frac{xd}{xd^\circ}$ are plotted on the y axis with time plotted on the x axis. The slope of the resulting line will be K_d. Figure 37 (82) depicts an example of the destruction of volatile solids and the analysis for obtaining the decay rate (K_d).

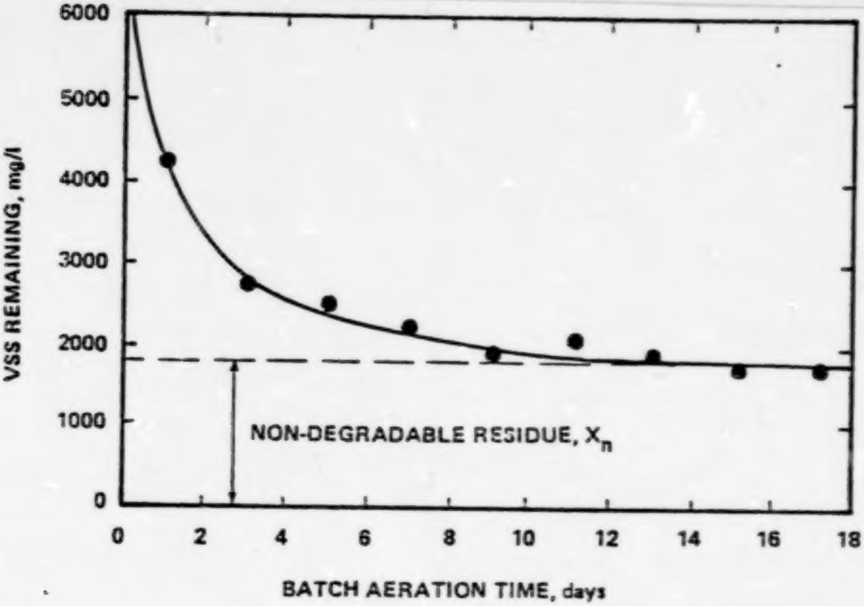
The reaction rate constant K_d is a function of sludge type, temperature, solids concentration. Figure 38 shows the effect of temperature on the reaction rate constant. It increases rapidly with temperature from 10°C to 40°C, and levels off from 45°C to 65°C. The data shown are for several different types of waste sludge, therefore, the curve only represents an average value of K_d. Also note that in Figure 38, no effort was made to correct K_d values for sludge age.

Reynolds (83) studied the effect of suspended solids concentration on K_d values for waste activated sludge and concluded that the reaction rate constant decreases with increasing suspended solids (Figure 39).

Jaworski et al (84) studied the effects of detention time and temperature on volatile solids reduction for the mixture of primary and activated sludge under aerobic digestion. Typical results are shown in Figure 40. Volatile solids reduction increases with increasing temperature (15-35°C) and detention time. Volatile solids reduction of 40 to 50 percent can be achieved at approximately 15 days detention time. Beyond that point, only slight increases of volatile solids reduction can be obtained. Also shown in Figure 40 is the effect of loading rate which varied inversely with the detention time in these studies. They suggested that the optimum loading, based on volatile solids reduction is approximately 0.1 lbs of volatile solids per cubic foot per day. Figure 41 (76) shows the effects of digester sludge age and temperature on volatile suspended solids reduction for waste activated sludge digested at low temperature. The reduction of volatile solids increases with increasing temperature to a maximum of 20°C. Even at 20°C, it took approximately 70 days to reach a 50 percent solids reduction indicating that waste activated sludge is more difficult to degrade than primary sludge, or their mixture. Hartman et al (77) studied the effect of temperature, ranging from 20 to 50°C, on volatile solids reduction of primary and trickling filter humus in batch aerobic reactors. The results are reported in Figure 42. At 30°C, volatile solids reduction reached 75 percent in approximately 25 days. Digestion temperatures higher than 30°C reduced the digestibility significantly. Figure 43 (3) shows the combined effect of temperature and sludge age on volatile solids reduction taken from many pilot and full scale studies of several types of municipal sludges. This curve indicates that a much slower increase in volatile solids removal above a product value of temperature and sludge age of about 250 for the temperature range studied.

Nitrification

In aerobic digestion, the nitrogen cycle follows from organic nitrogen to ammonia to nitrite and finally to nitrate. The degree of nitrification



(a) CHRONOLOGICAL DESTRUCTION OF VSS IN BATCH REACTOR

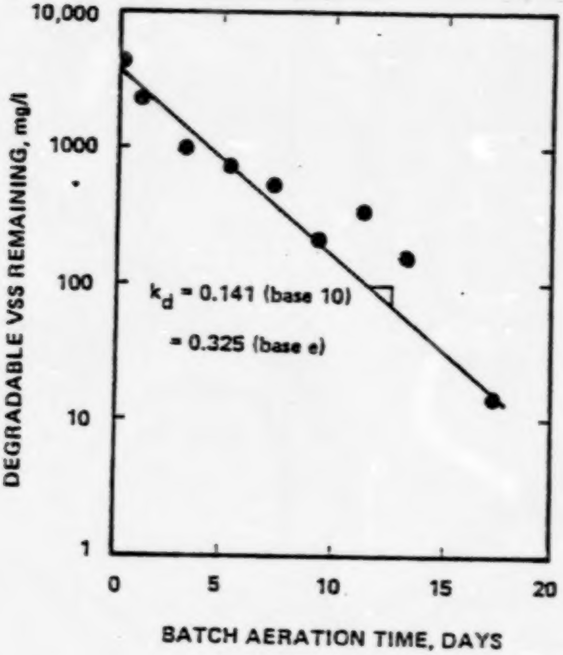


FIGURE 37. KINETICS OF AEROBIC SLUDGE DIGESTION. (82)

EPA Form 2350-6 (4-80)
TYPING GUIDE SHEET

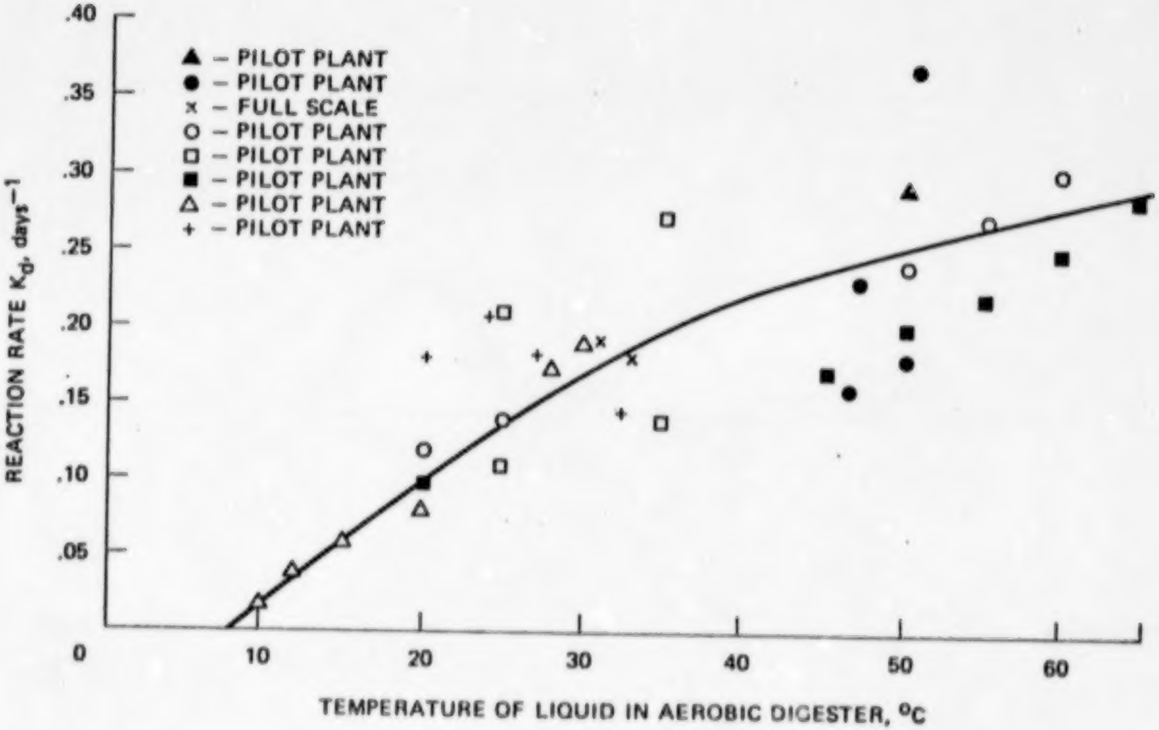


FIGURE 38 - REACTION RATE K_d VERSUS AEROBIC DIGESTER LIQUID TEMPERATURES. (3)

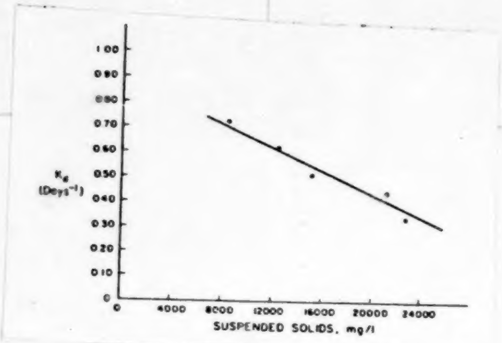


FIGURE 39 - K_d VERSUS SUSPENDED SOLIDS (83)

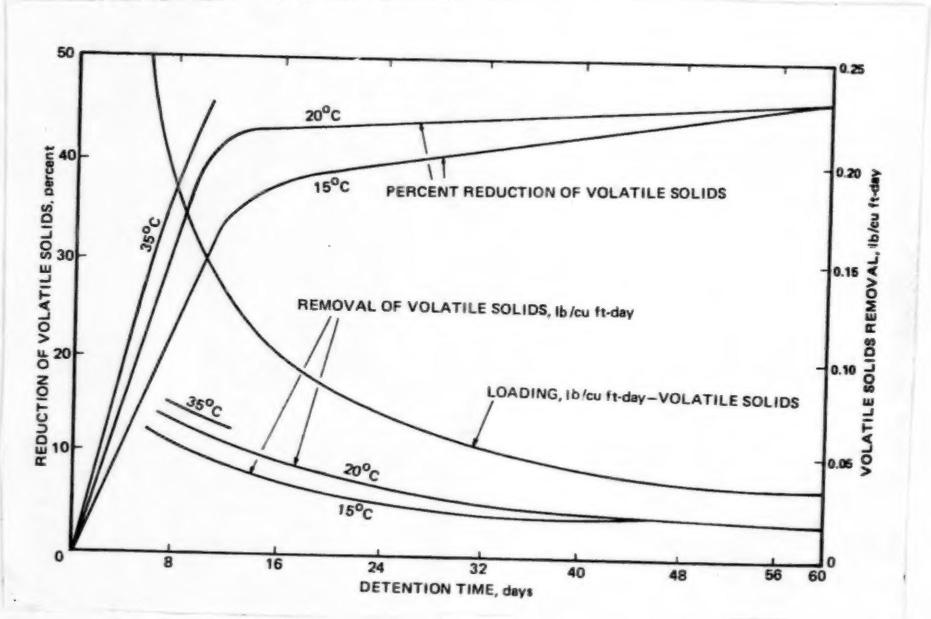


FIGURE 40 - EFFECT OF TEMPERATURE AND DETENTION TIME ON THE VOLATILE SOLIDS CONTENT OF AERATED SLUDGE (84)

BEGIN FIRST LINE OF TEXT HERE
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD: BEGIN SECTIONS HERE

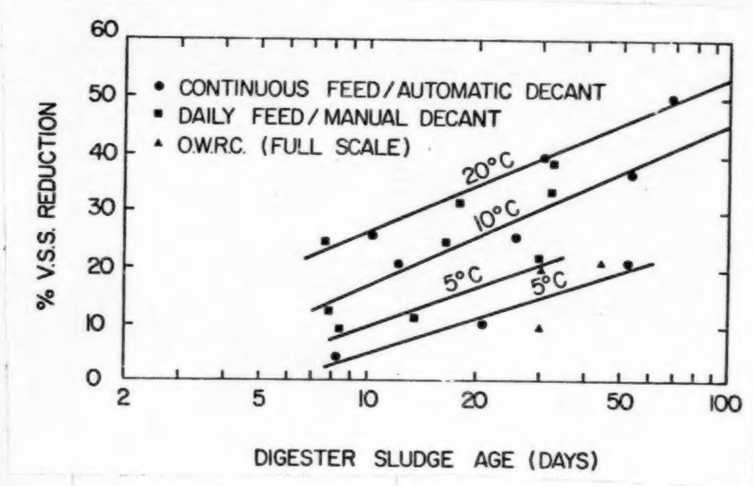


FIGURE 41 - EFFECT OF SLUDGE AGE ON VSS REDUCTION (76)

BEGIN LAST LINE OF TEXT
3/8"
BOTTOM OF IMAGE AREA, OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS

PAGE NUMBER
EPA Form 2350-4 (4-80)
[PREVIOUSLY CIN. EPA FORM 287]
☆ U.S. GOVERNMENT PRINTING OFFICE 1980-660-628
TYPING GUIDE SHEET

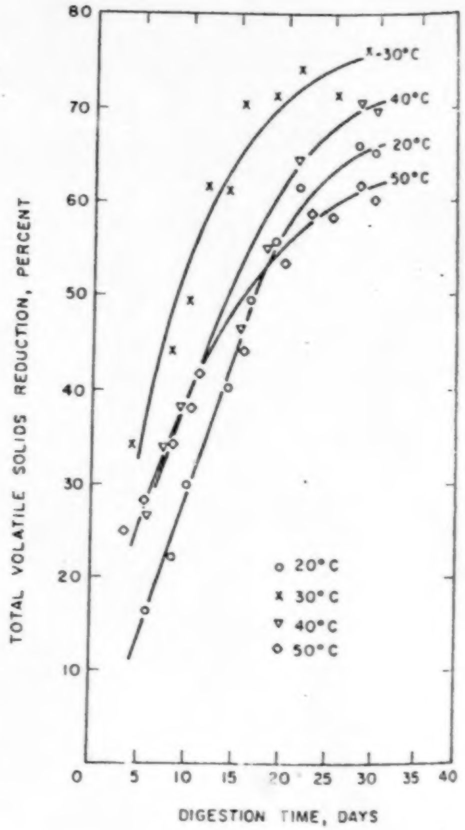


FIGURE 42. TOTAL VOLATILE SOLIDS REDUCTIONS AT VARIOUS OPERATING TEMPERATURES. BATCH DIGESTION OF A 2.6% TOTAL VOLATILE SOLIDS SLUDGE. (79)

EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN- EPA FORM 237)
TYPING GUIDE SHEET

BEGIN FIRST LINE OF TEXT HERE
CENTER OF PAGE
TOP OF IMAGE AREA
STOPPED HEAD; BEGIN SECTIONS HERE

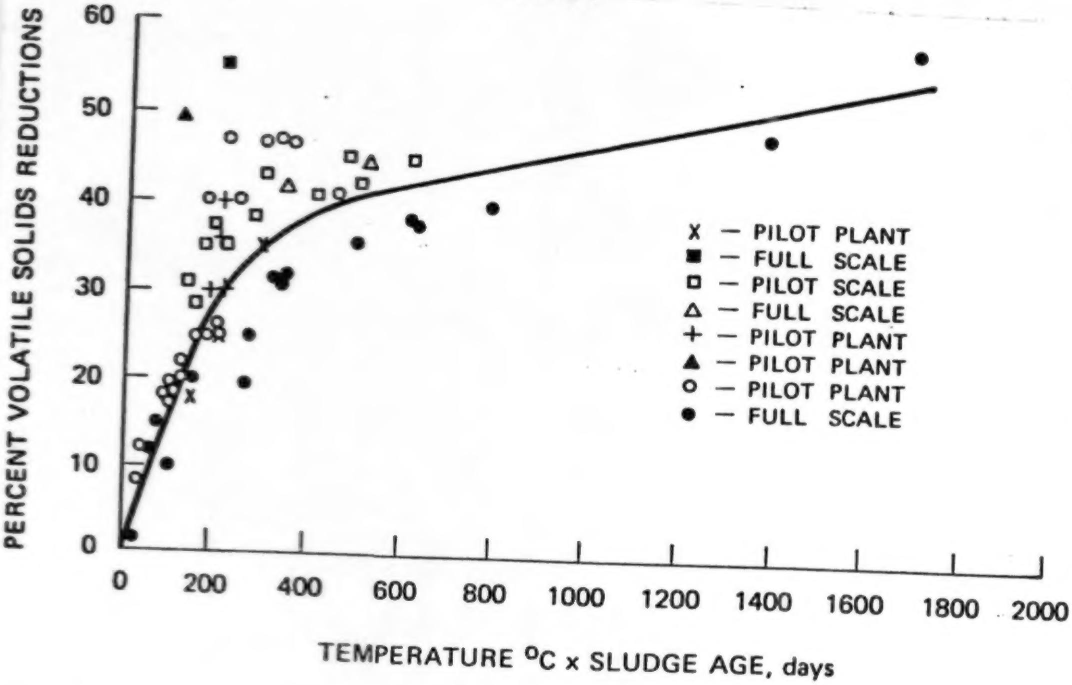


FIGURE 43. VOLATILE SOLIDS REDUCTION AS A FUNCTION OF DIGESTER LIQUID TEMPERATURE AND DIGESTER SLUDGE AGE. (3)

BEGIN LAST LINE OF TEXT
BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS

PAGE NUMBER
EPA Form 2350-5 (6-80)
(PREVIOUSLY ETL EPA FORM 287)
U.S. GOVERNMENT PRINTING OFFICE
TYPING GUIDE SHEET

may thus be a good indicator of stability under aerobic conditions. Jaworski et al (84) studied the relationship between ammonia, nitrite and nitrate in aerobic fermentation at various temperatures and plotted the results shown in Figure 44. The sludge under study consisted of a 1.75 to 1.00 ratio (dry solids basis) of primary and activated sludge. It is seen that more than 600 ppm nitrate-nitrogen was formed at a continually increasing rate to 60 days detention time, indicating that more organic and ammonia nitrogen were being converted to nitrate. As the ammonia was oxidized, both H^+ and NO_3^- were produced. Hydrogenions will then combine with HCO_3^- alkalinity to form CO_2 and H_2O. Some of the CO_2 will be stripped off and the result is a reduction in alkalinity. Figure 45 shows the alkalinity decreases from 700 ppm to less than 100 ppm in about 30 days at the temperatures studied. ThepH increased to approximately 8 in about 10 days, and then decreased gradually to values near 5. It is interesting to note that the pH and nitrite peaked and the ammonia reached a low at the approximate point where the solids destruction ceased.

Eikum (78) studied nitrification of primary sludge and he found that during aerobic digestion at different temperatures, the Kjeldahl-nitrogen decreased with increasing detention time and the loss was interpreted as the results of nitrification and denitrification. Figure 46 shows the decrease of Kjeldahl-nitrogen and the increase of NO_2^- and NO_3^- nitrogen. Also shown is the decrease of alkalinity with detention time.

Hartman et al (77) observed ammonia-nitrogen concentrations at high temperatures of 20, 30, 40 and 50°C and are shown in Figure 47. They found that the ammonia concentration increases during the initial stage of digestion then declines rapidly as nitrification ensues. A mixture of primary settled and trickling filter sludges was aerated in a series of five aerated reactors in bench scale work and a series of three reactors for pilot scale studies.

Adenosine Triphosphate (ATP)

Paterson et al (85,86) investigated the occurrence of adenosine triphosphate (ATP) in activated sludge as a measure of metabolic activity and/or biomass. Since ATP is a high energy compound in viable cells, it is more direct to express the cellular activity by the concentration of ATP than the standard parameter mixed liquor volatile suspended solids (MLVSS). Experiments conducted at the University of Florida with sludge taken from a contact stabilization plant indicated that only 15 to 20 percent of the MLVSS may be active biomass. ATP analyses on activated sludge samples from both batch fed and continuously fed laboratory units have consistently yielded ATP pools of 1.4 to 2.0 ug per mg VSS (85). Weddle et al (87) found that the ATP content of activated sludge solids increased with growth rate. At low growth rates (0.1-0.2 $days^{-1}$), the ATP concentration was in the range of 0.3-0.8 ug/mg VSS. While at high growth rates (2 $days^{-1}$), the ATP content appeared to reach a limit of 1.0 to 1.5 ug ATP/mg VSS. They also found that the ATP content per viable cell did not vary significantly over a growth rate range

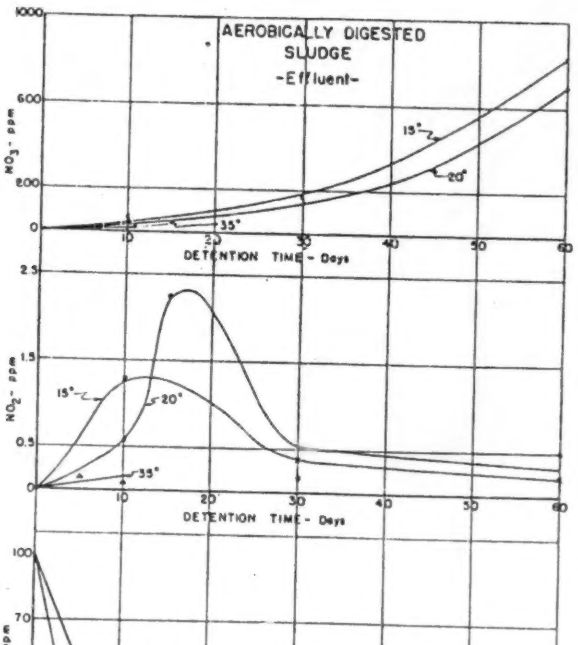


FIGURE 44. AMMONIA, NO_2, and NO_3 VERSUS DETENTION TIME. (84)

EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 287)
TYPING GUIDE SHEET

BEGIN FIRST LINE OF TEXT HERE
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD: BEGIN SECTIONS HERE

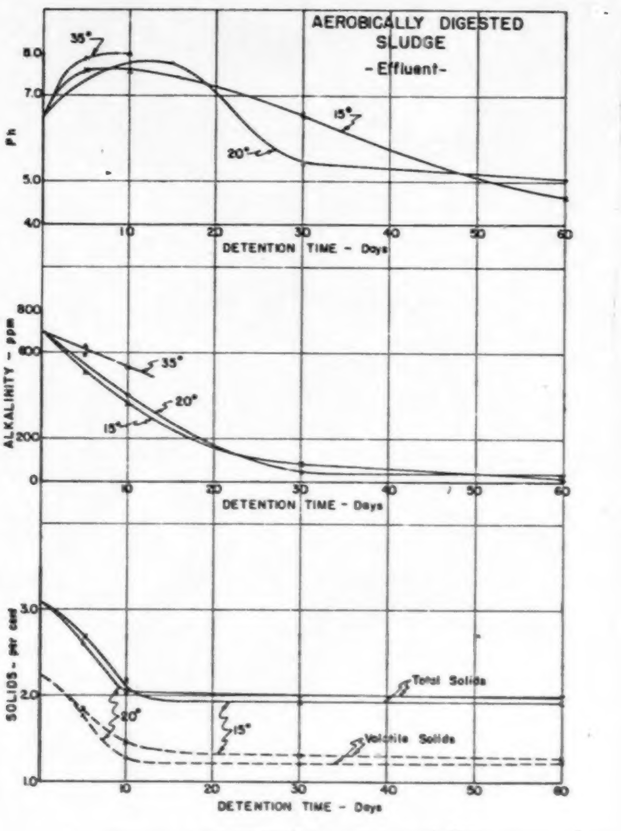


FIGURE 45. SOLIDS, ALKALINITY AND pH VERSUS DETENTION TIME. (84)

BEGIN LAST LINE OF TEXT
BOTTOM OF IMAGE AREA OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
3/8"

PAGE NUMBER
EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 327)
TYPING GUIDE SHEET

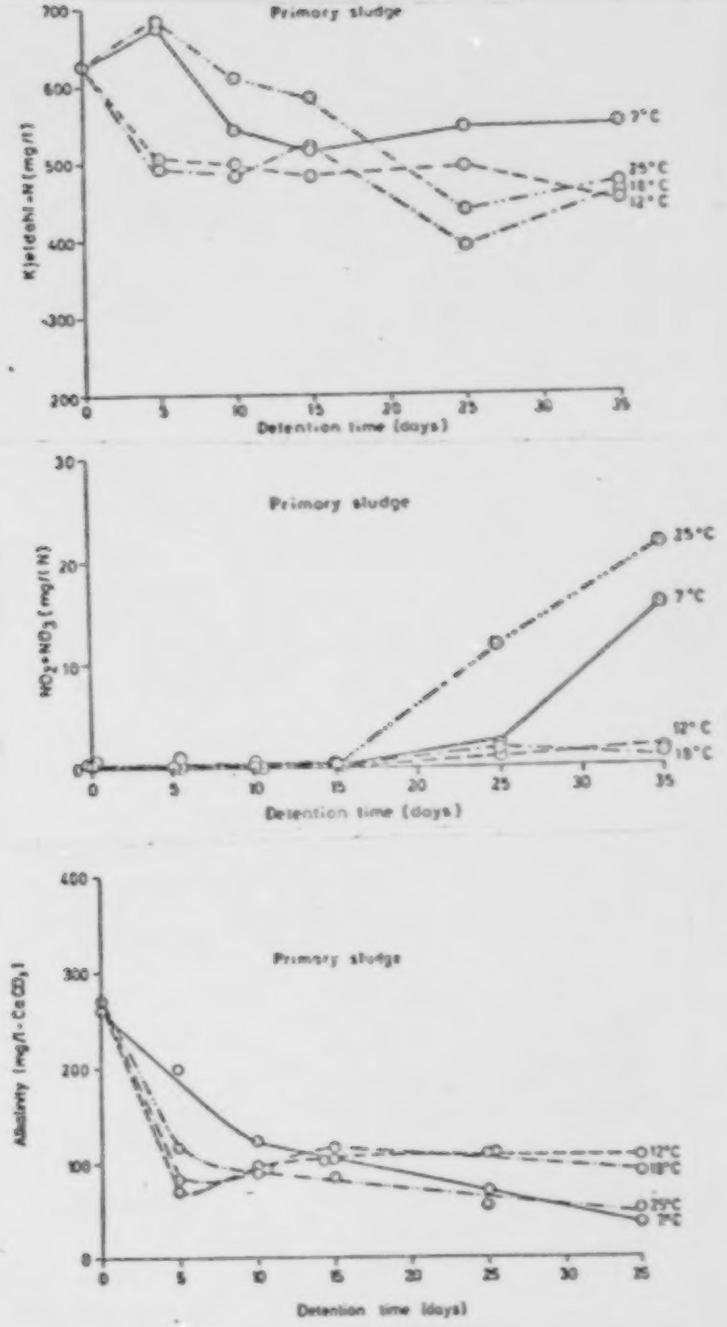


FIGURE 46. KJELDAHL-NITROGEN, NO_2 + NO_3-NITROGEN, AND ALKALINITY VS. DETENTION TIME. (78)

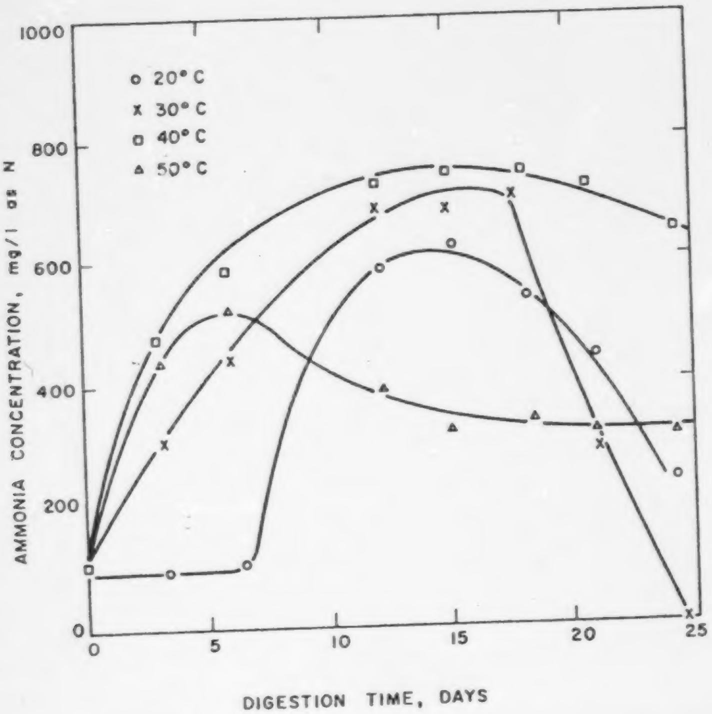


FIGURE 47. OBSERVED AMMONIA NITROGEN CONCENTRATIONS AT VARIOUS OPERATING TEMPERATURES. BATCH DIGESTION OF A 2.6% TOTAL VOLATILE SOLIDS SLUDGE. (77)

from 0.03 to 6.4 day^{-1}. The ATP content per viable cell was between 10^{-9} and 10^{-8} ug.

Eikum (78) studied the effects of temperature and detention time on the ATP pool for primary sludge associated with aerobic digestion. Figure 48 shows the viable portion of the volatile suspended solids increased from approximately 0.05 ug ATP/mg VSS in the raw primary sludge to a maximum value of 0.57 ug ATP/mg VSS at 25°C and 25 days detention time. At lower temperatures (7°C and 12°C), a lower maximum value of 0.27 ug ATP/mg VSS was obtained with a detention time of approximately 10 days indicating a smaller portion of the VSS will be viable cells. It was concluded that during aerobic digestion, a very low content of active cells are present in the volatile suspended solids.

It is possible to correlate the ATP and oxygen uptake rates with the stability of aerobically digested sludge. Since the ATP level will decline and stabilize when most organisms are in a very low energy or endogenous respiration state, this would correspond to a low oxygen uptake rate thus indicating the degree of sludge stability.

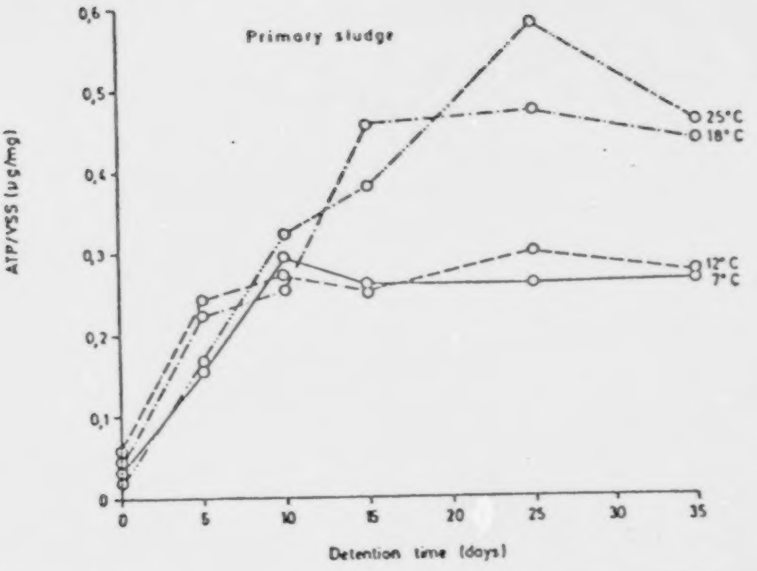


FIGURE 48. ATP/VSS VS. DETENTION TIME. (78)

EPA Form 2250-4 (4-80)
TYPING GUIDE SHEET

THERMALLY CONDITIONED SLUDGE

Thermal conditioning, in low and high pressure systems, involves heating of wastewater sludge to temperatures of 180 to 260°C (350-500°F) in a reation vessel under pressures of 1720-13790 k N/m^2 (250-2000 psi) for periods of 15 to 40 minutes. The main purpose of thermal conditioning a sludge is to change its physical character so that it can be dewatered more readily. With mechanical dewatering equipment following the thermal process, it has been reported that as much as 30 to 50 percent cake solids concentrations can be formed without adding chemical conditioners (88). Other advantages include (1) increasing volatile solids destruction in subsequent anaerobic digestion, (2) its suitability for treatment of many types of sludges than cannot be stabilized biologically because of the presence of toxic materials (3,89), and (3) the processed sludge is sterilized but is susceptible to recontamination). However, there are also disadvantages associated with this process. Among these are:

1. Production of an odorous gas stream which must be collected and treated before releasing.
2. A strong decant liquor stream composed of organic acids, ammonia nitrogen, sugars, polysaccharides, amino acids, etc. is produced depending on the characteristics of the feed sludge, reaction time and temperature.
3. The process may require heat energy and high cost in operation and maintenance expenses.

Brooks (90) studied the effect of temperature and heating time on the characteristics of activated sludge. Figure 49 shows the effect of temperature and reaction time on the settleability of heat treated activated sludge. The settleability at temperatures below 130°C was poor. However, temperature in the range of 163 to 197°C seemed to give excellent settleability. This was confirmed by the Buchner funnel tests. Samples heated to 100 and 130°C, even for 24 hours, were extremely difficult to filter through the filter paper because of the gelatinous nature of the sludge. Solids formed after heat treatment at 163°C and above were found to filter easily and produce greater than 40 percent solid cakes. At higher temperatures (163°C-197°C), heating times exceeding 0.5 hours seem to have minor effect on the settleability. Table 27 shows the effect of temperature and oxygen on the characteristics of 1 percent activated sludge.

It is interesting to note that a significant amount of suspended solids were solubilized into the liquid, thereby causing a large increase in dissolved solids. Both the organic and ammonia nitrogen concentration in the liquor increased after heat treatment due to the conversion of solid nitrogen forms to soluble forms. The effect of temperature on the fate of solids and nitrogenous compounds are shown in Figures 50 and 51 respectively. It can be concluded that thermal conditioning results in significant changes in the nature and in the composition of waste activated sludge. The high temperatures and pressures break down the cellular material found in sludge. Cell walls are ruptured and release protoplasm, proteinaceous matter, and suspended solids. The external cellular slime layer is also catabolized. The solubilized matter includes ammonia, volatile acids, and other organic

BEGIN FIRST LINE OF TEXT HERE
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD: BEGIN SECTIONS HERE

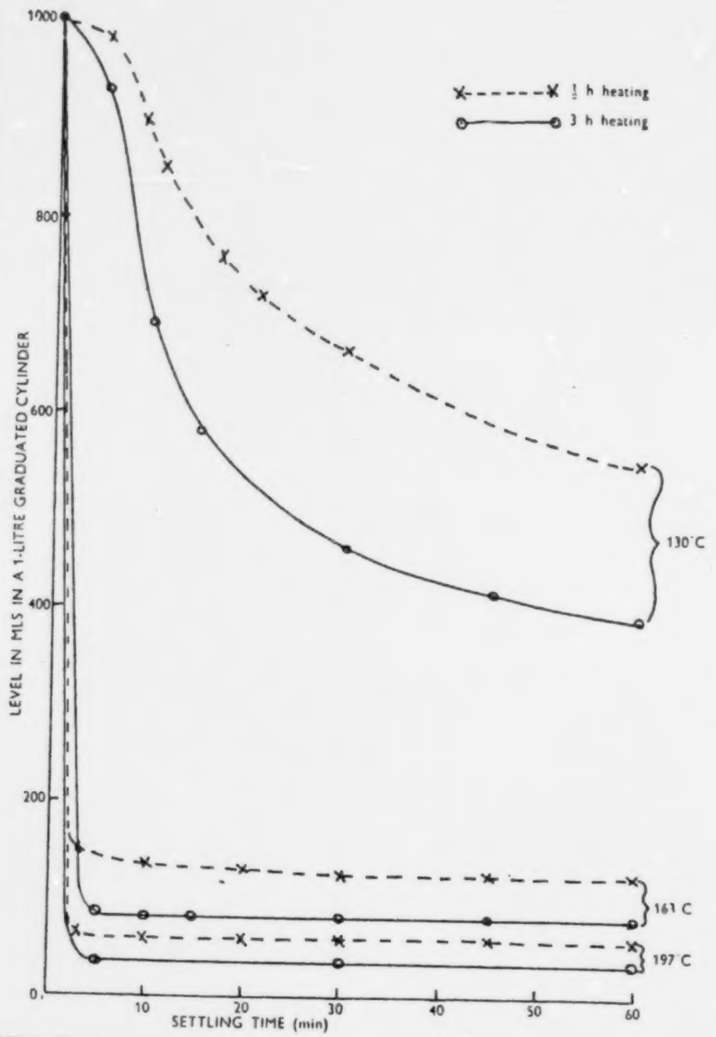


FIGURE 49. SETTLING CURVES OF HEAT-TREATED ACTIVATED SLUDGE. (90)

BEGIN LAST LINE OF TEXT
BOTTOM OF IMAGE AREA, OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
3/8"

PAGE NUMBER
EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 287)
U.S. GOVERNMENT PRINTING OFFICE 1980-660-600
TYPING GUIDE SHEET

TABLE 31. EFFECT OF HEATING 1 PERCENT ACTIVATED SLUDGE TO DIFFERENT TEMPERATURES FOR 1 HOUR WITH AND WITHOUT OXYGEN PRESENT (90)

Results, except where stated otherwide, in mg/1									
Temperature (°C)	Initial	100	130	163	197	100	130	163	197
Oxygen available.......	--	nil	nil	nil	nil	6200	6200	6200	6200
Chem. Oxygen demand....	--	3040	3660	5100	5450	3450	3990	5150	4950
Permanganate value:									
3 min..............	1.0	140	236	376	374	167	240	369	418
4-hour.............	2.8	344	593	920	1204	415	685	937	950
Organic N(liquid).....	0.04	247	389	462	452	282	375	413	328
Ammoniacal N (liquid).	0.25	21	41	103	172	31	66	158	293
Nitrogen in solid (per cent)..	7.82	7.13	6.24	4.4	3.93	6.88	6.28	4.21	3.48
Dissolved solids.....	500	3016	4194	4682	4348	3470	4204	4604	3510
Suspended solids.....	10000	6735	5300	4430	3205	7085	5110	3980	3575
Colloidal solids.....	30	3170	1260	700	360	2790	740	590	310
Total nitrogen.......	782	748	761	760	750	800	762	739	745
Total solids.........	10530	-	10754	9812	7913	-	10054	9174	7395
Total solids and volatile acids......	10530	-	10950	10201	8424	-	10300	9393	8230
pH value............	7.5	7.0	6.5	5.9	5.6	6.75	5.9	5.05	5.9
Total soluble phosphate..	--	-	-	31.6	9.8	-	-	18.6	4.9
Colour (5 mm cells)..	0	-	-	4.0	7.0	-	-	7.5	8.5

EPA-287 (Cin.)
(4-76)

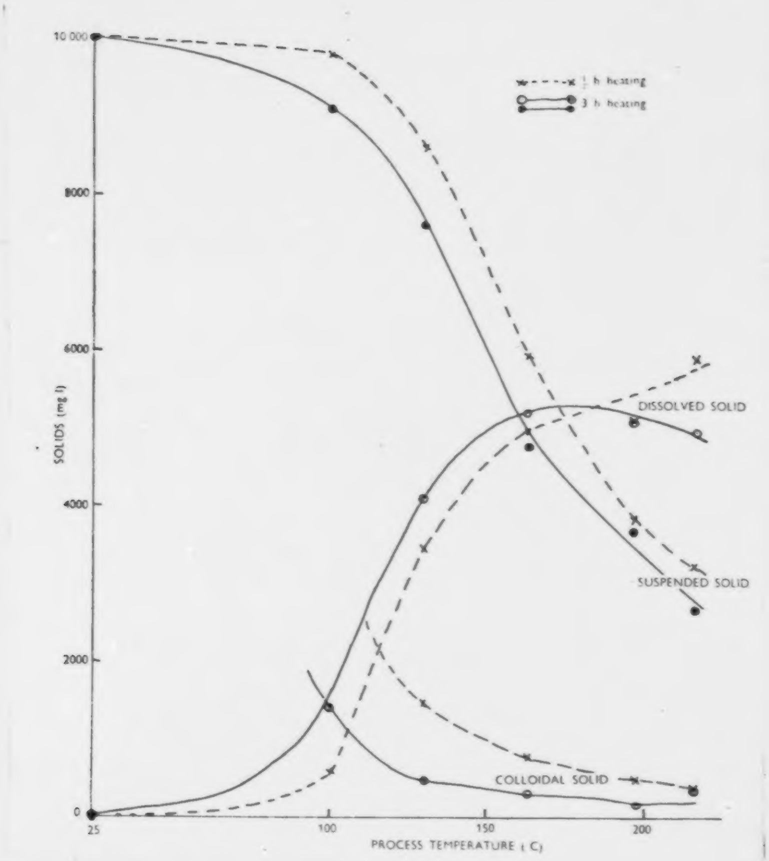


FIGURE 50. EFFECT OF PROCESS TEMPERATURE ON THE FATE OF SOLIDS DURING HEAT TREATMENT. (90)

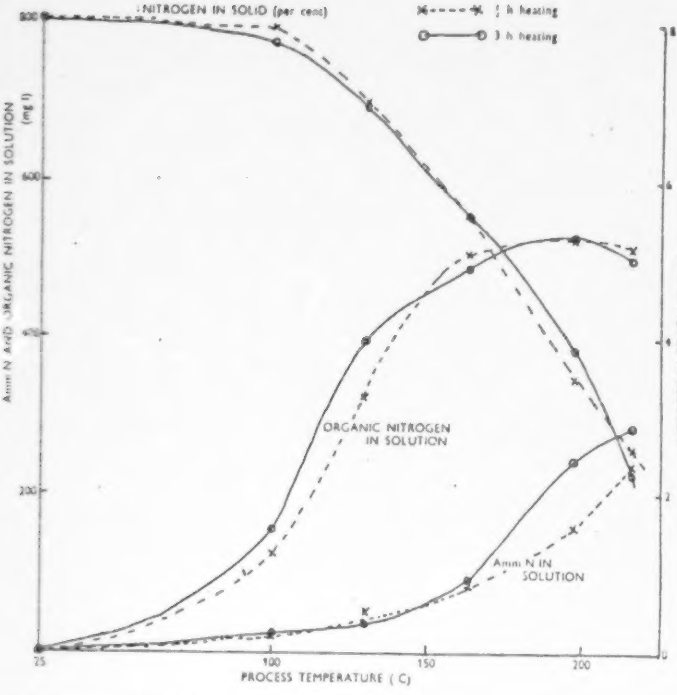


FIGURE 51. EFFECT OF PROCESS TEMPERATURE ON THE FATE OF NITROGENOUS COMPOUNDS. (90)

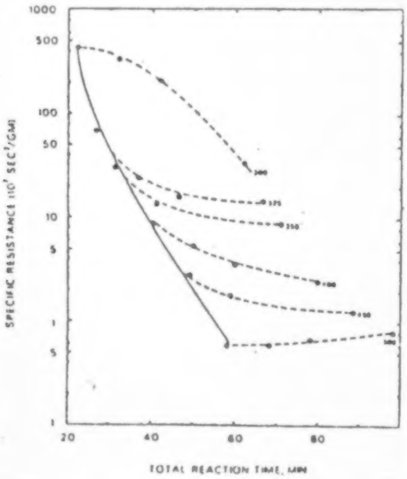


FIGURE 52. RESPONSE OF SLUDGE FILTERABILITY TO NON-OXIDATIVE THERMAL CONDITIONING. (91)

compounds. The resulting dark brown liquor is very high in COD and is very odorous. The dewatering characteristics of the solids are greatly improved.

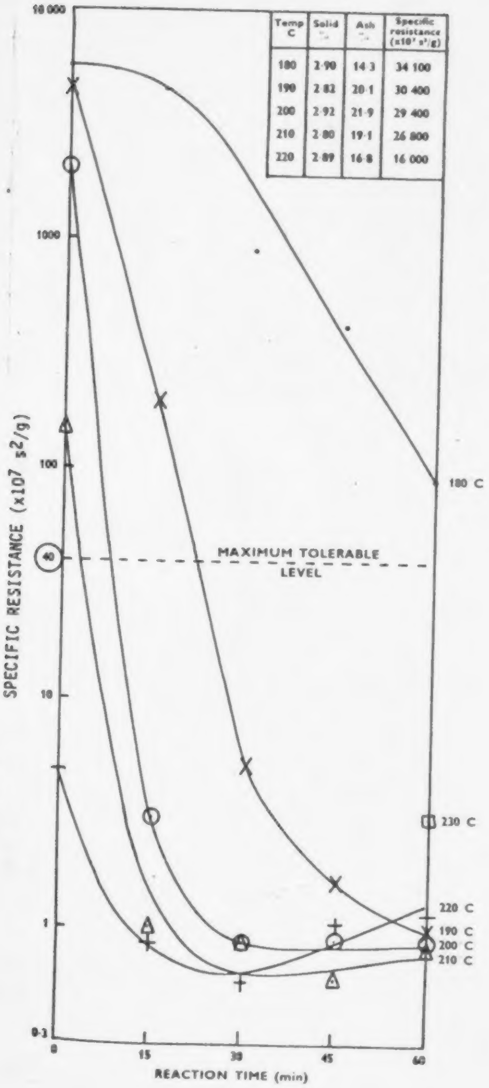
Marshall et al. (91) studied the filtration properties of heat treated activated sludge obtained from the biological waste treatment systems treating pulp and paper wastes. Figure 52 shows the effect of temperature and reaction time on the specific resistance of waste activated sludge. In order to eliminate any variation in specific resistance due to differences in solids concentration, the sludge concentration was maintained at one percent for comparison. Within the temperature range of 177 to 204°C (350 to 400°F) sludge specific resistance was reduced significantly to within 3-10 x 10^7 $\sec^2$/gm. This is well within the range for successful filtration. Brooks (92) compared the effect of temperature and reaction time on the specific resistance of activated, primary/activated, humus, and digested sludges as shown in Figures 53, 54, 55 and 56 respectively. All the sludges were standardized at approximately 3 percent solids concentration for comparison. These figures indicate that increasing temperatures and reaction times decrease the resistance to filtration. Figure 57 shows that increasing solids concentration causes an increase in the specific resistance of heat conditioned sludge. A similar variation in specific resistance was found when a sample was diluted to various concentrations with tap water after heat treatment.

Much of the methane production potential of residual organic materials is lost as a result of the inability of microorganisms to completely ferment them. Research by McCarty (93) has concentrated on increasing the biodegradability of lignocellulosic and nitrogenous materials. These materials are a major source of residual organics available for biological conversion to methane gas. Heat treatment of sludge seems to be a good method for increasing biodegradation However, in some cases, the products formed during heat treatment are toxic to methanogenic bacteria.

Lignocellulose is comprised predominately of cellulose, hemicellulose and lignin. Cellulose and hemicellulose by themselves are readily biodegradable, but when associated with the lignocellulose complex, they may be less than 50 percent available to microbial cultures. Heat treatment can break the lignocellulose complex. McCarty found that methane production was optimized with thermal pretreatment at 200°C at pH 13.

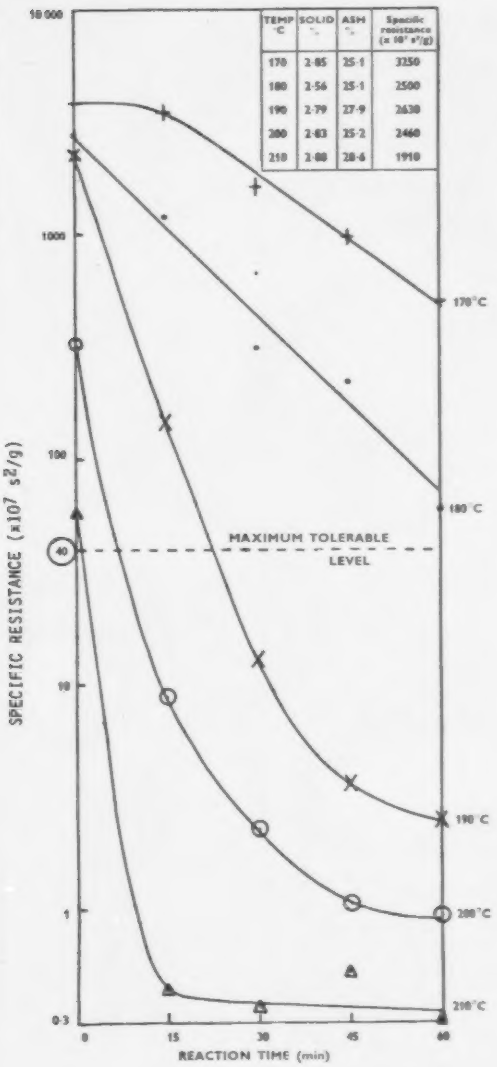
Microorganisms also have difficulty degrading nitrogenous materials. Nitrogenous organics are generally components of larger biological structures such as cell walls and cell membranes. At the optimum temperature of 175°C heat treatment increased the production of methane from nitrogenous organics. However, in order to take advantage of the increased biodegradability, the waste had to be diluted to prevent toxicity.

Because of the changes in the sludge nature and composition caused by heat treatment, digestibility of certain sludges is enhanced. Haug et al. (89) evaluated the effect of sludge heat treatment on undigested sludge. Experiments were conducted on primary sludge, waste activated sludge, and mixtures of both in two liter reactors. Thermal pretreatment of waste activated sludge yielded the most encouraging results. Methane production was



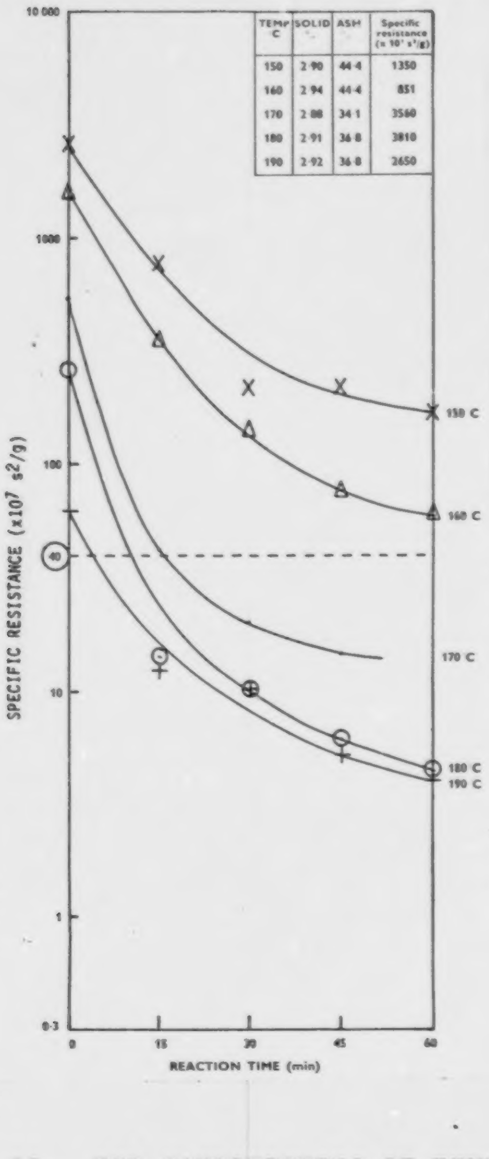
Temp C	Solid %	Ash %	Specific resistance (x10^7 s^2/g)
180	2·90	14·3	34 100
190	2·82	20·1	30 400
200	2·92	21·9	29 400
210	2·80	19·1	26 800
220	2·89	16·8	16 000

FIGURE 53. THE CONDITIONING OF ACTIVATED SLUDGE BY HEAT. (92)



TEMP °C	SOLID %	ASH %	Specific resistance ($\times 10^7$ s^2/g)
170	2·85	25·1	3250
180	2·56	25·1	2500
190	2·79	27·9	2630
200	2·83	25·2	2460
210	2·88	28·6	1910

FIGURE 54. THE CONDITIONING OF PRIMARY/ACTIVATED SLUDGE BY HEAT. (92)



TEMP C	SOLID %	ASH %	Specific resistance (x 10^7 s^2/g)
150	2·90	44·4	1350
160	2·94	44·4	851
170	2·88	34·1	3560
180	2·91	36·8	3810
190	2·92	36·8	2650

FIGURE 55. THE CONDITIONING OF HUMUS SLUDGE BY HEAT. (92)

BEGIN FIRST LINE OF TEXT HERE
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD BEGIN SECTIONS HERE
BEGIN LAST LINE OF TEXT
BOTTOM OF IMAGE AREA
EPA Form 2030-4 (4-80)
TYPING GUIDE SHEET

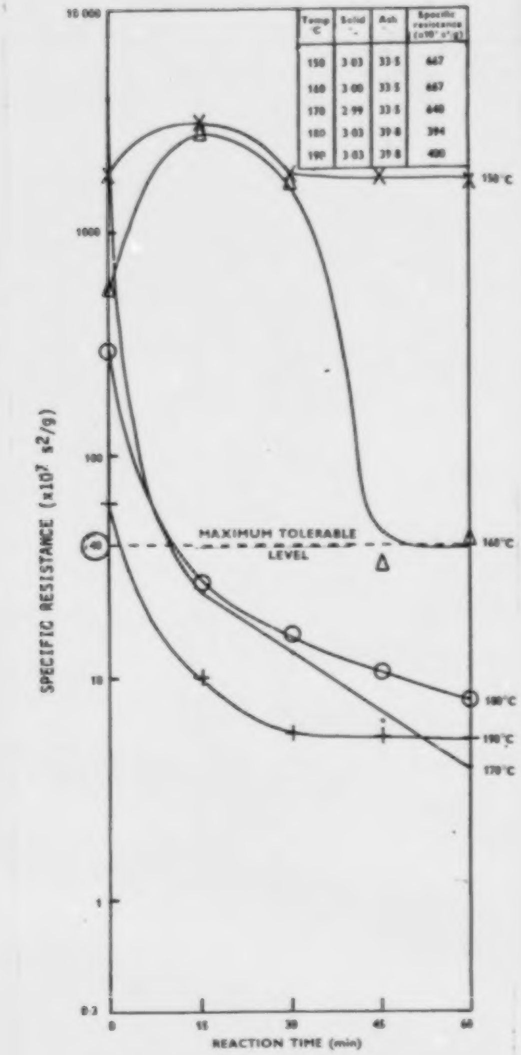


FIGURE 56. THE CONDITIONING OF DIGESTED SLUDGE BY HEAT. (92)

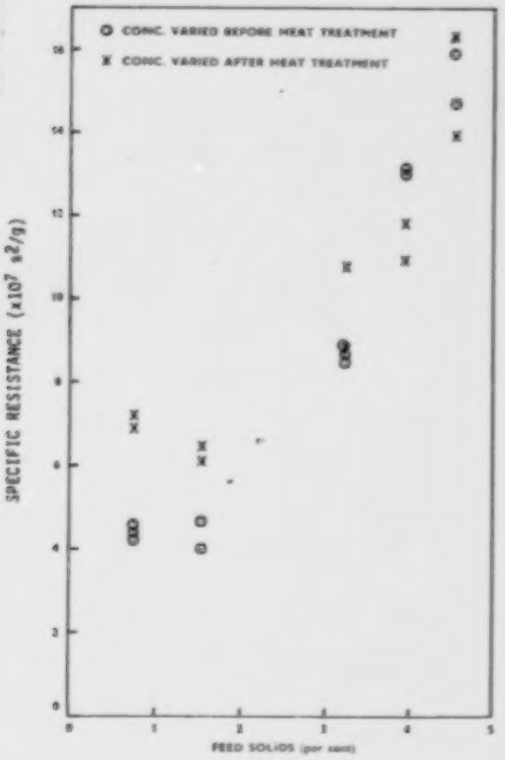


FIGURE 57. THE EFFECT OF SOLIDS CONCENTRATION ON THE SPECIFIC RESISTANCE OF HEAT CONDITIONED DIGESTED SLUDGE. (92)

increased 60%, and volatile suspended solids destruction increased 36%.

The County Sanitation Districts of Los Angeles (94) conducted an extensive study on sludges associated with themal treatment and anaerobic digestion. Both waste activated sludge and a blend of 65 percent primary and 35 percent waste activated sludge were investigated. The thermal conditioning unit was operated in the low pressure oxidation (LPO) mode: pressure was 2758 KPa (400 psig), 3.4 x 10^{-2} standard cubic meters per minute (1.2 scfm) of air was added, and the detention time was 29 minutes. Temperature was controlled at approximately 204°C (400°F). The digesters were operated on bench and pilot scale size. Both mesophilic and thermophilic sludge digestion were studied following heat treatment. The results are presented in Tables 32 and 33. In Table 32, it can be seen that except for the volatile solids destruction, the laboratory LPO conditioned waste activated sludge digesters did not perform as well as the control laboratory digesters for both mesophilic and thermophilic digestion. The volatile acids concentration was very high (2,200 and 1,830 mg/ℓ, respectively) and the gas production was poor. The high volatile solids destruction but low gas production in the LPO digesters was interpreted as the difficulty in establishing a stable methane forming bacterial population in the laboratory. However, the pilot scale digesters had low volatile acids concentration and much higher gas production than the laboratory digesters. It was concluded that the toxicity problems noted in laboratory tests as found by Haug et al. (89), were not encountered during pilot scale digestion. The results of a continuing LA/OMA study is given in Table 33 and show that the controls performed better than the LPO conditioned digesters.

CONCLUSIONS OF LITERATURE SURVEY

The scope of this literature review was confined to the stabilization of municipal sludges originating from aerobic and anaerobic biological processes and from thermal processes. Its primary objective was to review the literature, gather information on sludge instability and make it available to the scientific community and provide ideas for the laboratory work. In this context, therefore, it is essential to define a stable sludge. The best indicator of sludge stability is probably the inability of the sludge to degrade further biologically. For anaerobically digested sludge, parameters such as gas production, methane to carbon dioxide ratio, volatile solids reduction, ATP, BOD, COD concentration and others may be important parameters for measuring the potential for further biological degradation. Odor production potential could be very important in determining the stable state of a sludge. For example a sludge following 30 days of digestion will be less odorous than a sludge digested for 15 days. It is hoped to establish a simplified method for measuring sludge and relating it with other parameters discussed previously to obtain a sludge stability index.

For aerobically digested sludge, specific oxygen uptake rate, ATP, BOD, COD, organic nitrogen, ammonia nitrogen, nitrate, and others are important parameters measuring biological activity of the sludge. Operating parameters such as temperature, degree of mixing, organic loadings, solids retention time, and feed sludge characteristics are factors that also affect the stability of the product sludges.

TABLE 32. LA/OMA THERMAL PRETREATMENT STUDIES
COMPARISON OF DIGESTER PERFORMANCE
WASTE ACTIVATED SLUDGE

	LAB SCALE DIGESTERS				45.4 cu m (12,000) GALLON DIGESTERS		
Parameter	Control Meso	Control Thermo	LPO Meso	LPO Thermo	Control Meso	Control Therm.	LPO Therm.
VS Loading							
lb/ft^3 day	0.065	0.065	0.049	0.049	0.085	0.074	0.05
Kg/m^3 day	1.041	1.041	0.785	0.785	1.362	1.185	0.8
Detention time days	21	21	21	21	21	21	21
VS destruction	33%	41%	52%	56%	32%	39%	46%
COD Removal	36%	40%	30%	39%	33%	31%	43%
Volatile Acids mg/l	60	100	2200	1830	5	90	580
Gas Production							
ft^3/lb VS dest.	11.0	10.9	5.4	6.0	14.8	17.0	13.7
m^3/Kg	0.680	0.680	0.337	0.375	0.924	1.061	0.855
Methane Production							
ft^3/lb COD dest.	4.6	5.3	3.9	3.6	5.8	8.5	6.0
m^3/Kg	0.287	0.331	0.243	0.225	0.362	0.531	0.375

EPA Form 2350-4 (4-80)
TYPING GUIDE SHEET

TABLE 33. LA/OMA THERMAL PRETREATMENT STUDIES
LABORATORY SCALE ANAEROBIC DIGESTION (MESOPHILIC)
BLEND OF PRIMARY AND WASTE ACTIVATED SLUDGE
May 26, 1977-July 1977

Operating Parameters		I LPO Conditioned		II Control		III Control	
Digester Volume	liters	12		12		12	
Feed Rate	1/dy	.49		.49		.48	
Detention Time	days	24.4		24.4		24.4	
Volatile Solids Loading	$\frac{K_y}{m^3\text{-day}}$	0.592		0.817		0.817	
Volatile Solids Destruction	%	37.8		38.9		34.8	
COD Removal	%	50.6		46.6		51.8	
Gas Production	1/dy	1.2		4.5		4.5	
Gas Composition	% CH_4	50		67		64	
Gas Production	m^3/ky Vol.Sol.Dest.	0.456		1.180		1.317	
Methane Production	m^3/Kg COD Dest.	0.077		0.340		0.298	
Temperature	°F	96		96		96	
Constituents		**Influent**	**Effluent**	**Influent**	**Effluent**	**Influent**	**Effluent**
Total Solids	%	2.02	1.50	2.9	2.09	2.9	2.22
Volatile Solids	% TS	71.4	60.1	68.8	58.3	68.8	58.6
Volatile Solids	g/dy	7.07	4.41	9.77	5.97	9.77	6.37
Fixed Solids	g/dy	2.9	2.9	4.4	4.3	4.4	4.5
COD	mg/1 0	31,400	15,500	38,850	20,700	38,850	18,700
Soluble COD	mg/1 0	12,100	8,320	4,570	897	4,570	775
pH	Units	5.6	6.9	6.4	7.4	6.4	7.4
Volatile Acids	mg/1 CH_3COOH	1,700	2,920	850	132	850	188
Alkalinity	mg/1 $CaCO_3$	2,000	3,210	2,350	3,800	2,350	3,700

EPA Form 2350-4 (4-80)
TYPING GUIDE SHEET

SECTION 5

SOURCES AND TYPES OF MUNICIPAL SLUDGES USED IN OUR EXPERIMENTAL WORK

Sludges were obtained from eleven muinicipal treatment plants in New York State and New Jersey. These sludges included the following major types:

Extended aeration activated sludge
Aerobically digested activated sludge
Anaerobically digested primary sludge
Anaerobically digested activated sludge
Anaerobically digested primary and activated sludge
Anaerobically digested primary and trickling filter sludge
Thermally treated primary and activated sludges

As the source and pretreatment of these sludges may be important in the initial instability condition of the sludge, a brief description of the treatment plants follows.

AEROBIC SLUDGES

Six different aerobic sludges were studied from six municipalities. They range in size from small extended aeration plants of 0.4 mgd flow to a large 85 mgd plant. The following are descriptions of the treatment plants from which sludges were obtained and Tables 34 and 35 give a summary of the treatment plant major parameters.

Beacon, New York

Beacon has an activated sludge plant with typical primary and secondary settling. Recycle is returned to the aeration tank from the secondary clarifier. The activated sludge wasted is aerobically digested. The plant was designed for 6 mgd but during the period the samples were taken the average daily flow ranged from 1.9-5.2 mgd which is the typical summer dry weather flow. The operator estimates the flow includes about 1 mgd of industrial process water. Dyes from two industries cause occasional colored influents but are not believed to cause toxicity problems. Good operating results were being obtained at the time the sludge was taken for the studies. The food to mass loading factor of the aeration tank was about 0.4 (F/M = 0.4) with an average aeration detention time of 8.8 hours. The F/M ratio was typically computed based on 30% BOD_5 removal by the primary clarifier. Waste activated sludge is fed daily to the aerobic digestion tank which has a six day detention time. The sludge sample studied was taken from this aerobic digestion tank. The sludge is then pumped into a thickener where it is mixed with primary clarifier sludge. Following thickening it is incinerated.

Cold Spring, New York

Cold Spring has primarily a domestic wastewater with a contributor population of approximately 2300 people. The average flow to the extended aeration treatment plant is about 0.45 mgd. with peaks to about 0.91 mgd. Its design capacity is 0.50 mgd. The treatment process includes aerated grit chambers, extended aeration tanks, secondary clarifiers and effluent chlorination. Extended aeration averages close to one day detention time and the study sample was taken from this treatment unit. The food to mass ratio is about 0.046.

Musconetcong Sewerage Authority, New Jersey

Between 0.8 and 0.9 mgd of primarily domestic water is treated at the Musconetcong treatment plant. About 0.3 mgd is treated in a Can-Tex prefabricated contact stabilization unit and the remaining flow by a conventional activated sludge plant. In these studies, sludge from the Can-Tex plant was used.

The Can-Tex plant treatment sequence consists of aeration for about five hours followed by clarification. Settled sludge is reaerated for 12 to 24 hours and is returned to the aeration tank for further contact. Once daily, sludge is pumped from the clarifier into the aerobic digester. Each week the air supply to the aerobic digester is shut overnight and in the morning the supernatant is withdrawn. About one-third of the sludge is withdrawn to a holding tank. Thus the aerobic digestion time is approximately 21 days. Overall, the plant is very well run with BOD_5 and suspended solids removal running higher than 90 percent.

Following aerobic digestion the sludge goes to a holding tank prior to vacuum filtration. Sometimes it remains for days in the holding tank and anaerobic reactions take place. Odors arise during vacuum filtration, especially during warm weather.

Stony Point, New York

Stony Point has a one mgd extended aeration treatment plant. The waste water is primarily domestic in nature. This facility includes an aerated grit chamber followed by a splitter box for distribution of recycle activated sludge and wastewater to the four extended aeration basins. No primary settling tanks are incorporated in the treatment plant. Secondary settling follows extended aeration and the settled sludge is recycled to the splitter box at the head end of the aeration tanks. When the mixed liquor suspended solids are high in the extended aeration tank, settled sludge is wasted to one of two aerobic digesters. It digests aerobically for an additional 2 to 3

TABLE 34. SUMMARY OF TREATMENT PLANT OPERATIONAL PARAMETERS FOR THE ACTIVATED SLUDGES USED

August 1980	BOD_5 mg/ℓ		Sus. Solids mg/ℓ		Ave. Flow mgd	Aerator		Ratio F/M	Aeration Time hrs.	Aerobic Digestion Time days
	Inf	Eff	Inf	Eff		MLSS mg/ℓ	Volume mg			
Beacon, N.Y.	191	24	75	23	3.15	910	.386	0.40	8.8	6
Cold Spring, N.Y.	214	1.4	117	6.5	0.45	4180	0.5	0.046	27	
Musconetcong, N.Y.	248	19	252	24	0.30	4730(A) 8740(R)	.064	0.047	5.1(A) 12-24(R)	21
Stony Point, N.Y. (summer)	187	23	214	27	0.69	3000	1.0	0.062	34.8	7
Stony Point, N.Y. (winter)										
Nov. 1980 Avg.	192	22	199	25	0.67	3000	1.0	0.064	35.8	14

TABLE 35. SUMMARY OF TREATMENT PLANT OPERATIONAL PARAMETERS FOR THE THERMAL SLUDGES

August 1980	BOD_5 mg/ℓ		Sus. Solids mg/ℓ		Ave. Flow mgd	Aerator		Ratio F/M	Aeration Time hrs.	Aerobic Digestion Time days
	Inf	Eff	Inf	Eff		MLSS mg/ℓ	Volume mg			
Rockland County, N.Y.	144	18	164	20	14.7	1150	2.48	0.21	3.9	-
Poughkeepsie, N.Y.	60	12	83	5	4.1	946	1.35	0.13	7.9	-

(A) - Contact aeration tank

(R) - Reaeration tank

weeks before discharge onto sand drying beds. A three inch depth of aerobic sludge dries very nicely during warm months but a six inch layer will not dry well and causes odors. Winter drying may also produce odors as the sludge will not dry rapidly and tends to build up.

The average flow into the plant during the periods when the sludge samples were collected were 0.69 and 0.67 mgd during August and November, 1982 respectively. The influent and effluent BOD_5 were 187 and 23 in August and 192 and 22 mg/ℓ respectively during Novembver, 1982. Based on this information the F/M ratio was calculated as about 0.06.

Sludge from the aerobic digester was used as seed during this study. The seed samples were obtained on August 20th and December 3rd of 1980. The average August and November temperatures were 23 and 15°C respectively.

Rockland County, N.Y. Sewer District No. 1

The Rockland County wastewater treatment plant was designed to handle a 10 mgd flow but was averaging about 14.7 mgd at the time of the sampling. This secondary treatment plant has step aeration activated sludge with primary and secondary clarification. Aeration time at the 14.7 mgd flow rate is 4.1 hours. Waste activated sludge is pumped to the head of the primary clarifiers from where it is pumped to thickeners as a mixture of primary and secondary sludges. From the thickening process the sludge is pumped into anaerobic digesters or directly into the Zimpro wet oxidation process. Anaerobic treatment of the sludge mixture is maintained at 95-100°F with a total detention time of close to 30 days in the two stage digesters. Mixing of the first stage digester is accomplished using draft tube mixers. The second digester is not mixed.

Sludge enters the Zimpro thermal process through a sludge storage tank and then into the wet oxidation reactor. Compressed air is combined with pressurized sludge at a pressure of about 800 psi. The influent temperature of the reactor is about 390°F and the treated sludge exits at close to 470°F. Sludge for the study was taken from the bottom of the decant tank which follows the thermal reactor. The decant tank supernatant is returned to the treatment plant influent while the sludge is cooled, dewatered on a vacuum filter and the cake is disposed on a land fill site.

Poughkeepsie, New York

Poughkeepsie has a secondary plant for wastewater treatment and is composed of aerated grit chambers, primary settling, mechanically aerated activated sludge and secondary settling. The plant was designed for a flow of 8 mgd and at the time of sampling was operating at an average of 4.1 mgd. Industrial wastewater flow is relatively small but there are a number of fabric dyeing operations which contribute sufficient dye to make the wastewater rather colorful at frequent intervals. The wastewater is rather weak in character averaging less than 100 mg/ℓ for both BOD_5 and suspended solids. Aeration detention time (excluding recycle) is approximately 7.9 hours with a F/M ratio of 0.13. Waste activated sludge is returned to the primary clarifier where it is thickened with the raw sludge in the clarithickener section of the clarifier. The plant manager estimates the thickened sludge to be about 50 percent each of activated and raw sludges. Thickened sludge is pumped to the sludge holding tank and then into the Zimpro thermal treatment process. Operating conditions of the process are 310-330 psi pressure at a temperature of 355-360°F. A treated sludge holding tank follows the reactor and a bottom sludge sample was taken from this tank for analysis. Heat treated sludge from the bottom of the holding tank is centrifuged and the solids cake was being landfilled at the time the sample was collected. Decant from the holding tank and the centrate are returned to the head of the plant. Table 36 summarizes the characteristics of the sludge for the month of August 1980.

TABLE 36. POUGHKEEPSIE, N.Y., SLUDGE CHARACTERISTICS

Sludge Location	Percent Total Solids	Percent Volatile Solids
Clarithickener eff. (Zimpro Inf.)	2.2	89.0
Zimpro effl.	1.9	75.1
Centrifuge inf. (Zimpro settled eff.)	14.3	57.9
Centrifuge cake	36.7	57.9

ANAEROBIC SLUDGES

Seven anaerobic sludges from five municipal wastewater treatment facilities were studied in this investigation. Averages of the pertinent treatment plant operational data are given in Table 37 for the month of November 1980 for all but one of the Cedar Creek sludges in which the August 1980 data are included. These averages were chosen as being the most representative of the contents of the digesters when the samples were taken for study.

TABLE 37. SUMMARY OF TREATMENT PLANT OPERATIONAL PARAMETERS FOR THE ANAEROBIC SLUDGES

November 1980	BOD_5 mg/ℓ		Sus. Solids mg/ℓ		Ave. Flow mgd	Aeration Time hrs.	Ratio F/M	Anaerobic HRT & SRT days	Loading lbs VS/ cf·d	% VS Destroyed
	Inf	Eff	Inf	Eff						
26th Ward, New York City	71	12	81	17	83	3.0	0.19	19	0.11	42
Coney Island, New York City	136	62	146	84	100	2.3	1.94	24	0.18	56
Cedar Creek, New York	164	36	169	87	26	4.5	0.33	34	0.07	54
Oyster Bay, New York	105	18	83	26	1.9	-	73*	37	0.04	62
Yonkers, NY (Primary sludge)	169	6	135	7	77	4.3	0.81	13	0.31	51
Yonkers, NY (waste activated sludge)	169	6	135	7	77	4.3	0.81	18	0.08	27
Cedar Creek, New York (August 1980)	164	22	208	46	26	4.4	0.14	35	0.07	49

* Trickling filter organic loading 1b BOD_5/1000 CF-day

New York City, New York - 26th Ward Plant

The 26th Ward water pollution control plant is a step aeration activated sludge plant with an average flow of 85 mgd. Primary sedimentation, four-pass aerators and secondary clarification comprise the major units for treatment of this municipal wastewater. Sludges from the clarifiers are gravity thickened, digested anaerobically and disposed into the Atlantic Ocean. Aeration of the four-pass aerators is accomplished using fine bubble diffusers. Each of the bays is 404 feet long by 30 feet wide and 15 feet deep and a total usable volume of 1,380,000 cubic feet. The average detention time is almost three hours at an organic loading of 49 pounds BOD_5 per 1000 cubic feet per day.

Anaerobic digestion of the primary and waste activated sludge was accomplished in two heated (95°F) 86 foot diameter primary digesters followed by two secondary digesters of equal diameter. The primaries have 30 feet side water depth while the secondary are 29 feet deep. The cone depth is 9 feet. The volumes of the primary and secondary tanks are 191,500 and 186,000 cubic feet each respectively. The digesters have fixed covers, are equipped with external sludge heaters and are continuously mixed using gas recirculation. The average hydraulic and solids detention time is 19 days. Organic loading averages 0.11 pounds of volatile solids per cubic foot per day. Following digestion the sludge enters a holding tank from which it is barged out to sea.

New York City, New York - Coney Island Plant

Coney Island has a 100 mgd modified aeration secondary municipal wastewater treatment plant. The system includes grit removal, modified aeration (no primary settling), and secondary sedimentation. Grease is collected but it is not anaerobically digested at this plant or at any of the city treatment facilities. Approximately 2.3 hours aeration is provided by modified aeration and the organic loading is 89 pounds BOD_5 per 1000 cubic feet per day. Four aerators containing two passes each are used.

Sludge from the secondary clarifiers is gravity thickened to 8 to 9 percent solids and is then digested anaerobically in four 71 foot diameter primary tanks. The digesters are fixed cover, continuously mixed using gas recirculation and heated using external heat exchangers to about 98°F. Following primary digestion the sludge is pumped into a secondary storage digester from where it is pumped to a dock facility for barging to sea. The digesters have an organic loading of 0.18 pounds of volatile solids per cubic foot per day with a 24 day hydraulic detention time.

Nassau County, New York - Cedar Creek Plant

Nassau County's Cedar Creek secondary treatment plant has a design capacity of 45 mgd and during the time of these studies was operating at 31 mgd. About 5 mgd was being diverted for advanced wastewater treatment in a separate train of treatment units. The secondary plant unit operations consist of aerated grit removal, primary clarification, step aeration activated sludge and final clarification. Disinfection is provided during the warm months of the year.

The primary sludge is pumped directly to anaerobic digesters while the waste activated sludge is provided air flotation for thickening before an aerobic digestion. Digestion is accomplished in two 105 foot diameter primary digesters with almost two million gallons capacity each. Approximately 45 days hydraulic detention time is provided. These two digesters are continuously mixed using gas recirculation while heating to about 95°F is accomplished using external heat exchangers. Both digesters have floating covers.

Following primary digestion the sludge enters one secondary digester. As no separation takes place, the secondary digester merely serves as a holding tank and further digestion. A smaller holding tank follows the secondary tank from which it is pumped to the Bay Park treatment facility for barging to sea.

Oyster Bay, New York

Oyster Bay has a secondary wastewater treatment facility employing high rate trickling filters. The major process components include grit removal, primary settling, trickling filters and secondary sedimentation. Recycle of secondary sedimentation effluent is employed at a usual rate of approximately 0.9 to 1.0 recycle to raw flow respectively. The sludges from the primary and secondary clarifiers are digested anaerobically. Two 70 foot diameter trickling filters with six-feet of 3 to 6 inch crushed trap rock are used which treat the 1.93 mgd average flow. Sludge from the secondary clarifier is returned to the primary clarifier for further thickening prior to digestion.

Anaerobic sludge digestion equipment includes a primary digester, a secondary digester, vacuum filter and glass covered drying beds. Sludge from the primary clarifier is pumped into the 35 foot diameter primary digester. Temperature is maintained at about 92-93°F by recirculation of sludge through a heat exchanger. Raw and trickling filter sludges entering the digester are preheated in the exchanger. The liquor operating level in the primary digester is 25 feet, yielding a volume of 180,000 gallons. A Perth gas recirculation system provides mixing for about 9 hours each day and a floating cover is used. Approximately 4900 gpd of the mixture of primary and secondary sludges was being pumped daily into the digester for a 37 day detention time and 4900 gallons of supernatant was transferred to the secondary digester each day. Once every two weeks primary digested sludge of about 7 percent total solids was transferred from the bottom of the primary digester to the secondary digester. This was the source of sludge for the experiment.

The secondary digester has a diameter of 35 feet and maximum operating sludge liquor level of 22.5 feet, providing a volume of 160,000 gallons. It acts as a quiescent holding tank with supernatant return by gravity to the primary clarifier.

Westchester County, Yonkers, New York

Municipal treatment facilities for most of the wastewater of Westchester County is treated at the Yonkers Joint secondary plant. Treatment consists of aerated grit removal, primary sedimentation, activated sludge step aeration, secondary sedimentation and chlorine disinfection (during the warm months of the year). The flow averages about 77 mgd.

Sludges from the primary clarifiers was provided anaerobic digestion in two heated digesters of 900,000 and 560,000 gallons capacity each. This sludge is prethickened before digestion using picket type thickeners. The digesters were being fed approximately 116,000 gallons daily for a detention period of close to 13 days. Following digestion the sludge enters a holding tank from which it is pumped onto a barge and hauled out to sea for final disposal. Both digesters have fixed covers and are mixed using a gas recirculation system.

Waste activated sludge was thickened using air flotation and digested in five anaerobic digesters of 718,000 gallons capacity each. They are of the fixed type with gas recirculation for mixing and employ external heat exchangers for heating. About 205,000 gallons per day of waste activated sludge were being fed to these digesters for an average of 18 days detention time.

SECTION 6

EXPERIMENTAL PROCEDURES AND APPARATUS

DESCRIPTION OF APPARATUS

Anaerobic Digesters

The purpose of our work was to determine how stable a sludge is and the point where a sludge may be considered stable. In this laboratory work, simulation of field conditions was attempted, but some field conditions could not be duplicated. Obviously, our reactors had to be much smaller than full scale installations. Initially our anaerobic reactors contained 18 liters of sludge. Mixing these reactors also may not be representative of actual field conditions. A vigorous complete mix was used. Hence, the reactors had a higher power to reactor volume ratio than typically found in actual treatment plants. Another important difference between the reactors and those found in treatment plants is the feeding schedule. Treatment plant digesters are fed on a regular basis, while our reactors were never fed.

The reactors were maintained at a temperature of 35°C, which is typical of full scale digesters. The reactor consisted of a 20 liter pyrex aspirator bottle sealed with a rubber stopper (Figure 58). The rubber stopper had two openings. One opening was connected to a wet test gas meter, and the other was used for mechanical mixing. The mixing apparatus consisted of a length of tygon R3603 tubing 0.953 ID cm x 1.429 OD cm (3/8" ID x 9/16" OD) sealed at the bottom by doubling over, and bound with copper wire. The upper end of the tube extended beyond the top of the stopper and was left open. A 0.318 cm (1/8") bent steel drill rod approximately 60 cm (23.6") was inserted into the tube and the remaining space between the tube and the rod was filled with vegetable oil. A Barber Coleman Byqm-33510-12 DC gear head motor was used to drive the mixing rod. Speed was controlled by varying voltage to the motor. Gear heads on these motors deteriorated after several months continuous use, and needed to be replaced. These motors were replaced by RAE Model 101921 gear head AC-DC type motors. Speed was controlled at about 150 RPM using a variable transformer. These motors proved very successful in use. The rod was connected to the motor by a chuck which made servicing and access to the reactor simple.

The tygon tube used for mechanical mixing was replaced on a regular basis to prevent its breaking and leaking of vegetable oil into the reactor. Approximately once every six weeks proved to be an adequate replacement time.

Gas samples were removed through a glass tee on the exhaust gas line equipped with a rubber septum. Liquid samples were removed through the aspirator opening. Gas samples were obtained using a 1 ml gas tight syringe, and injected directly into the gas chromatograph. In addition to the 18

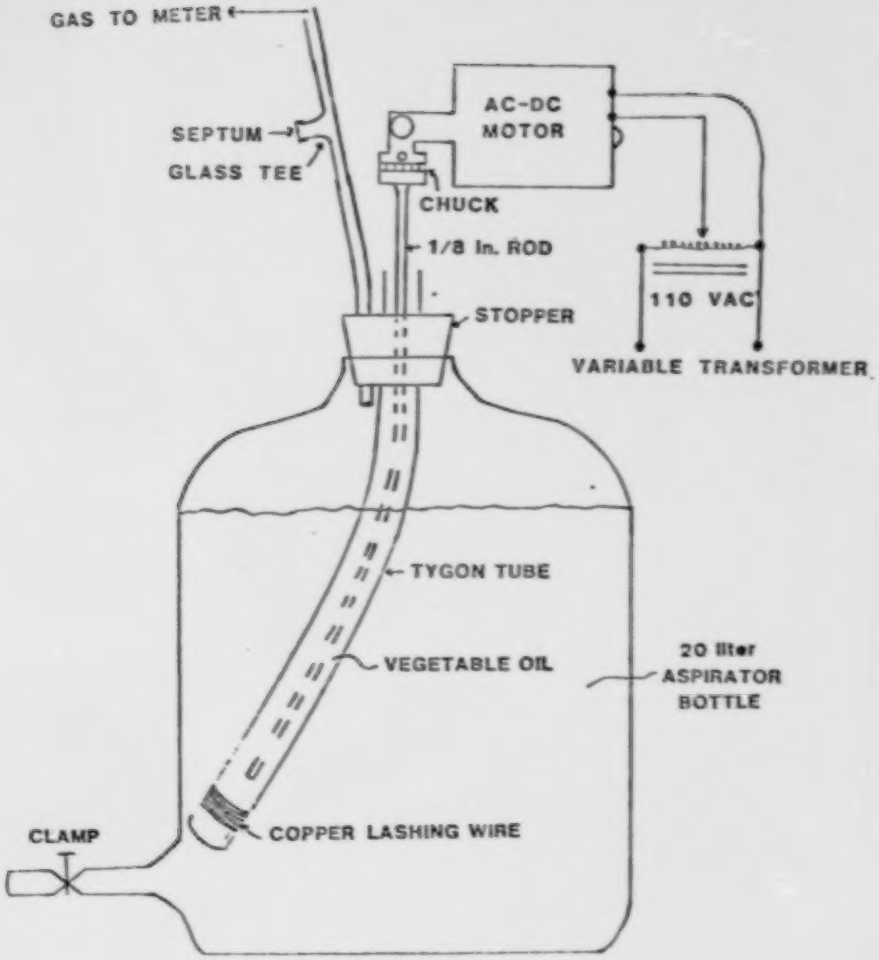

GAS TO METER
SEPTUM
GLASS TEE
AC-DC MOTOR
CHUCK
1/8 In. ROD
STOPPER
110 VAC
VARIABLE TRANSFORMER
TYGON TUBE
VEGETABLE OIL
20 liter ASPIRATOR BOTTLE
COPPER LASHING WIRE
CLAMP

FIGURE 58. Continuously Mixed Anaerobic Reactor Schematic

liter reactors, 1.5 liter reactors were also set up. The major differences between the 18 liter and 1.5 liter reactors are mixing, sampling, and gas measurement. The 18 liter reactors were mixed continuously, while the 1.5 liter reactors were mixed by hand once daily. The 1.5 liter reactors were not sampled on a regular basis.

Gas production was measured using 1300 ml glass collection cylinders attached to the 1.5 liter reactors with tygon tubing as shown in the schematic drawing in Figure 59. To insure a low solubility for carbon dioxide, the confining fluid was composed of a saturated solution of sodium chloride in 10% sulfuric acid. In order to facilitate the readings of gas volume, the confining fluid was colored using methyl orange. All anaerobic reactors were kept in a walk-in room in which the temperature was held constant at 35°± 1°C. Heat was supplied by a portable electric heater.

Aerobic Digesters

Aerobic reactors used in our study consisted of 19 liter (5 gallon) fish tanks equipped with porous stone air diffusers (Figure 60). Air flow rates were regulated to assure complete mixing. These tanks were covered and water was added to compensate for evaporation.

Some important differences existed between the bench scale laboratory reactors used in the study and the aerobic digesters in full scale operation. Although no temperature control was used in our aerobic studies, the bench scale reactor temperature variance was limited to the ambient temperature of the laboratory (20-26°C). Full scale aerobic digesters at the locations from which the samples were taken are operated at lower temperatures than found in the laboratory. Another important difference between the bench scale reactors and full scale operations is the feeding schedule. Full scale aerobic digesters may or may not be fed on a regular basis, while the bench scale reactors were never fed.

The amount of air input into our bench scale reactors was probably not representative of full scale operations. No measurement of gas flow rates were made during the course of the experiment. However, flow rates to maintain good mixing on the lab scale most likely exceeded rates found in full scale operations.

ANALYTICAL TECHNIQUES

Samples were removed from the laboratory reactors five times weekly during the first six weeks of the study, and then as required for the remainder of the study. The size of the sample was determined by the volume of sample required for the tests to be performed on that day. On some days an excess of sample was removed and preserved for future analysis. Sludge stability was monitored by testing for a variety of parameters on a regular basis, and observing changes with respect to time.

BEGIN FIRST LINE OF TEXT HERE
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD; BEGIN SECTIONS HERE

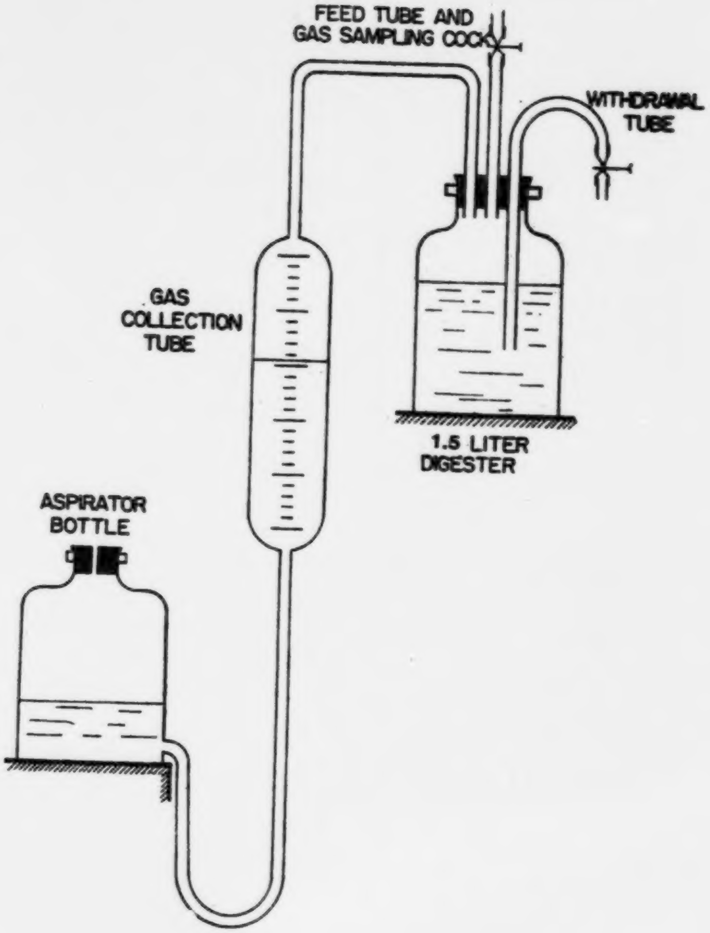

FEED TUBE AND GAS SAMPLING COCK
WITHDRAWAL TUBE
GAS COLLECTION TUBE
1.5 LITER DIGESTER
ASPIRATOR BOTTLE

FIGURE 59. SCHEMATIC LAYOUT OF 1.5 LITER REACTOR

BEGIN LAST LINE OF TEXT
BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
3/8"

EPA Form 2250-4 (1-80)
PAGE NUMBER
TYPING GUIDE SHEET

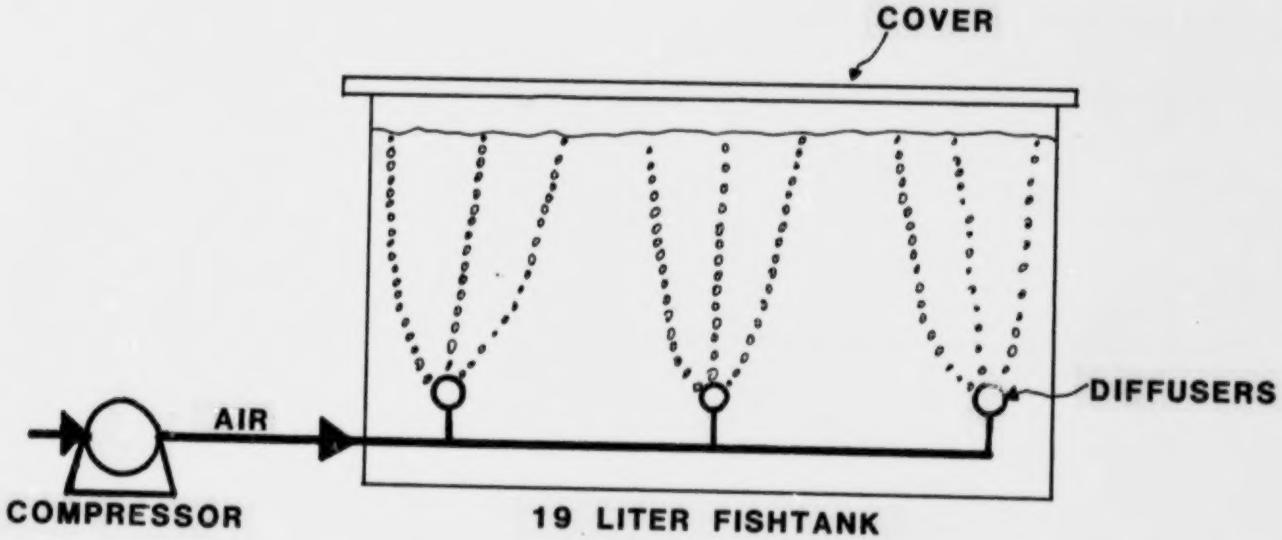

COVER
DIFFUSERS
AIR
COMPRESSOR
19 LITER FISHTANK

FIGURE 60. Aerobic Reactor Schematic

Standard Analyses

Many of the conventional tests used by environmental engineers as well as some new testing procedures were performed on the samples. The majority of tests performed were in accordance with Standard Methods for the Examination of Water and Wastewater 14th Edition 1975. Procedures for some of the tests performed were found in the literature, and in a few cases were adapted as necessary based on laboratory experience. A complete list of all tests performed and methods used are given in Table 38.

ATP Measurement

Although a significant effort was extended to ATP measurements, no ATP data is given in this report because of difficulties encountered in the analyses. First, the Aminco photometric instrument arrived later than promised and the project had been started. Due to inexperience with the analysis and a defective photometer, the analyses proved to be unsatisfactory. A new instrument was received but unfortunately, the procedure was not mastered in time to make the needed analyses. The following describes the procedures that were used.

A number of methods for measuring adenosine triphosphate (ATP) appear in the literature as well as bulletins from instrument manufacturers and reagent distributors. The first method used in our study required the extraction of ATP from cells by boiling the cells in tris buffer. During our study Tris extracted ATP samples were analyzed using the internal standardization procedure. Unfortunately, the procedure followed did not allow a sufficient concentration difference between the sample and background lumenescence and the data collected was not satisfactory. Because of this difficulty and the time consuming nature of the Tris buffer extraction procedure, a new procedure recommended for better results was adopted.

The procedure followed was an adaptation of the method recommended by Lumac Systems, Inc. This method was chosen because of its utilization of the internal standardization principle in which the relationship of ATP in the sample to light intensity emitted by the sample is linear. However, the dynamic range of the instrument used to measure light intensity may distort the linearity of this relationship in certain ranges. The microphotometer used in our analysis had a dynamic range of approximately five decades.

Since our measurements were made on sludge, turbidity was present in our samples. If a calibration curve was generated using an ATP standard, turbidity would be negligible when compared to a sample containing sludge. Since turbidity absorbs light and light emission is the basis of our results, erroneous results caused by turbidity need to be accounted for. The internal standardization procedure accounts for turbidity in samples when standardizing. In this procedure, standardization is made by mixing a known amount of ATP with the sample and measuring luminescence. The sample is then measured with no additional ATP. By subtracting the amount of luminescence given off by the sample, the amount of ATP in the presence of the sample is known. Any quenching of light energy by turbidity in the sample is therefore corrected for by standardizing in the presence of the sample. This procedure is repeated for every sample.

Apparatus

a) Microphotometer - A Chem-Glow Photometer (Model J4-7441) was used for all of the analysis. This model features a reaction chamber containing the photomultiplier tube which permits sample injection through a rubber septum into the cuvette. This enables sample measurement immediately after the bioluminescent reaction begins.
b) Strip chart recorder - A Cole Parmer (Model 8376-30) recorder was used to measure bioluminence peak heights. Best results are obtained using an electronic intergrator timer.
c) Cuvettes - 6 x 50 mm, Kimble products No. 73500

Reagents

All reagents used were purchased from Analytical Luminescence Laboratory, Inc.

a) Purified firefly extract (Luciferin-Luciferase) - This reagent emits light when mixed with ATP, Mg^{++} and oxygen. Analytical Luminescence markets this as "firelight".
b) Hepes buffer, pH 7.75 (firelight buffer) - this buffer is used to reconstitute the purified firefly extract.
c) ATP standard - adenosine triphosphate in pure form is required for standardization of the instrument.
d) ATP extraction reagent (extralight) Lumac NRS or NRB. This reagent is used to release ATP from cells.

Procedure

a) Background Correction -
    1. Place 100 uℓ of distilled water, and 200 uℓ of extralight into a cuvette and mix.
    2. Place cuvette into microphotometer and inject 100 uℓ of firelight.
    3. Read peak value from recorder.
    4. Perform analysis in triplicate and record average as x_{Blank} or x_B.

b) Sample Measurement
    1. Place 200 uℓ of sample at the proper dilution into a cuvette, Note: Sample peak height should be 1/2 to 1/5 the reading obtained when 200 uℓ sample is mixed with 10 uℓ ATP STANDARD SOLUTION. (x_Δ = 1/2 to 1/5 x_B).
    2. Add 200 uℓ of extralight to cuvette and mix
    3. Place cuvette into microphotometer and inject 100 uℓ of firelight
    4. Read peak value from recorder
    5. Perform analysis in triplicate and record average as x_A

c) Internal Standard

1. Place 200 uℓ of sample at proper dilution into 3 cuvettes and add 10 uℓ of ATP standard
2. Repeat steps 2 through 4 from above
3. Perform analysis in triplicate and record average as x_B

$$\frac{\text{ATP}}{\text{Luminesce Unit}} = k = \frac{\text{ATP ADDED (ug)}}{x_B - x_A}$$

$$\text{ATP in sample} = k(x_A - x_B)$$

$$\text{No. of cells} = \frac{\text{ATP in sample}}{\text{ATP per cell}}$$

Centrifuge Button

One of the major causes of odor problems associated with sludges is the production of hydrogen sulfide gas (H_2S). Hydrogen sulfide is produced by a species of bacteria known as desulfovibrio. These organisms utilize various sulfur compounds as final electron acceptors in their oxidation of various organic compounds. Since hydrogen sulfide has a repugnant odor, detection of hydrogen sulfide produced by sludges would indicate that the sludge is unstable with respect to odor. Hydrogen sulfide may be detected by lead acetate paper, as the paper is discolored in the presence of hydrogen sulfide. This procedure closely follows the technique described by Hartman et al. (79).

Procedure followed in Phase I of project:

1) Sludge samples were taken as identified in Figures 61 and 62.
2) Place 50 mℓ of the sludge into a centrifuge tube, centrifuge at 5000 RPM for 15 minutes.
3) Decant off most of the supernatant leaving a small amount to keep the sludge wet (about 3 mℓ).
4) Cap tube with a rubber stopper having a slit cut on its bottom to hold lead acetate paper.
5) Incubate tubes at 35°C until discoloration occurs.
6) Record time at which discoloration occurs.

In Phase II of the project the anaerobic sludges were diluted to 1% solids and the aerobic sludges to 0.5% solids. This was done to make the solids concentration uniform in all the centrifuge tubes set-up and eliminate the effect of varying solids from tube to tube. Also, the amount of discoloration of the lead acetate paper used to define the end point of the experiment was decreased to about 10% blackening of the area of the paper in order to increase the sensitivity of the test. In Phase I, greater than 50% of the paper was blackened when a test was considered completed.

As will be discussed later, the Phase I procedure gave consistent results with few points that appear out of order. However, the procedure used in

TABLE 38. ANALYTICAL METHODS

Analysis	Schedule	Method pH	Equipment
pH	2/week	Standard Methods (SM) (Ref 46)	Orion Model 701A Digital Ionalyzer
Alkalinity	2/week	(SM); endpoint titration, Anaerobic pH 4.0	Orion Model 701A Digital Ionalyzer
Specific oxygen uptake rate (sour)	2/week	(SM); oxygen consumption rate	YSI Model 54 Oxygen Meter
Total solids	2/week	(SM); total residue dried at 103-105°C	NAPCO Model 410 Oven
Total suspended solids	2/week	(SM); total non-filterable residue dried at 103-105°C	Millipore Filter Apparatus NAPCO Model 410 Oven
Volatile solids	2/week	(SM); total volatile and fixed residue at 550°C	Thermolyne Model F-A1740 Muffle Furnace
Volatile suspended solids	2/week (aerobic only)	(SM); volatile and fixed matter in non-filterable residue and semisolid samples	Thermolyne Model F-A1740 Muffle Furnace Millipore Filter Apparatus
Dissolved solids	2/week (aerobic only)	(SM); total filterable residue residue, dried at 103-105°C	Millipore Filter Apparatus
Conductivity	2/week	(SM); conductivity	Industrial Instruments Model RC 16B2 Conductivity Bridge

TABLE 38. (cont'd)

Analysis	Schedule	Method	Equipment
BOD	1/week	(SM); Oxygen demand (biochemical), membrane electrode method	YSI Dissolved Oxygen Meter Model 54
Nitrate	1/week	(SM); nitrate, cadmium reduction method	Bausch & Lomb Spectronic 20 Spectrophotometer
Ortho-Phosphorus	1/week	(SM); stannous chloride method	Bausch & Lomb Spectronic 20 Spectrophotometer
Total Phosphorus	1/week	(SM); preliminary digestion steps for total phosphorus stannous chloride method	Bausch & Lomb Spectronic 20 Spectrophotometer
Volatile acids	1/week (anaerobic only)	(SM); Chromatographic separation method for organic acids	Chromatographic column
Grease and oil	1/2 weeks	(SM); oil and grease extraction method for sludge samples	Soxhlet extraction apparatus
Total Kjeldahl	1/week	(SM); Nitrogen (organic) macro-Kjeldahl method	Kjeldahl digestion rack
Ammonia Nitrogen	1/week	(SM); nitrogen (ammonia) titrimetric method	Ammonia distillation rack

TABLE 38. (cont'd)

Analysis	Schedule	Method	Equipment
Lignin	1/month	Forage fiber analysis Agriculture Handbook No. 379 U.S.D.A.	As specified in handbook
COD	1/week	Ref. 95	
ATP	Variable	See Section-Analytical Techniques, ATP Measurement	
Centrifuge Button		See Section-Analytical Techniques, Centrifuge Button Ref. 79	
Buchner Funnel	1/2 week	Ref. 96	
CST	1/2 week	Ref. 97	Capillary Suction Time Apparatus, Triton Electronics, Model WPRL Type 130

Phase II, which was intended to be an improvement over the Phase I procedure, proved unsatisfactory. The data points obtained were so inconsistent that they were of no value. The reason for these poor results was most likely the change from 50% to 10% blackening to indicate instability. It is believed that 10% blackening of the lead acetate paper is not a sufficient indicator of hydrogen sulfide. Continuing studies eventually showed that on a number of occasions, the edges of the lead acetate paper would discolor (about 10% of the paper) and show no increase in blackened area for long periods of time. In such cases, the result based on 10% of the area being blackened, would indicate an unstable sludge at an early time whereas if 50% of the area were to be blackened, the time required would be much longer.

Lignin

In the experimental phase of the project, analyses for lignin were attempted. The analysis is rather long and tedious requiring a significant amount of laboratory training. Because of the limited experimental time available, the procedure was not satisfactorily developed to yield meaningful results.

EXPERIMENTAL PROCEDURE

The experimental procedures employed were designed to extend the biological digestion process far beyond where it is normally terminated in conventional digestion processes. Completely mixed anaerobic digesters typically have detention times of about 20-30 days. In our study, sludge taken from such conventional digesters was further digested for more than 100 days. Aerobic digesters have detention times on the order of 10 to 20 days. Sludge taken from aerobic processes was further digested an additional 100 days.

All laboratory reactors were seeded using sludges obtained from treatment plants in the New York Metropolitan area. During the course of our study, a total of 13 anaerobic and 9 aerobic reactors were set up and monitored in our laboratory. Anaerobic reactors 1 through 6 and aerobic reactors 1A through 6A were analyzed during the first phase of the study. Anaerobic reactors 7 through 13 and aerobic reactors 7A through 9A were analyzed during the second phase of the study.

Figures 61 through 64 illustrate the scheme by which our various aerobic and anaerobic reactors were prepared. For example, Figure 61 shows the various anaerobic reactors which were prepared during the first phase of the study. In the first box in the upper left hand corner, the one indicates the reactor number. Cedar Creek, New York 25% raw indicates that 25 percent of the reactor contents is raw sludge taken from the Cedar Creek plant. The 75% seed indicates that 75 percent of the reactor volume is seed. Figure 61 shows that the seed is digested primary and activated sludge from the Cedar Creek plant. Reactor four contained 100% seed and may be used for seed corrections and was used to seed the other reactors.

In Figure 62 time of digestion and type of digestion process is indicated on the figure. For example, unit 1A was taken from an aerobic digestion process having a detention time of six days.

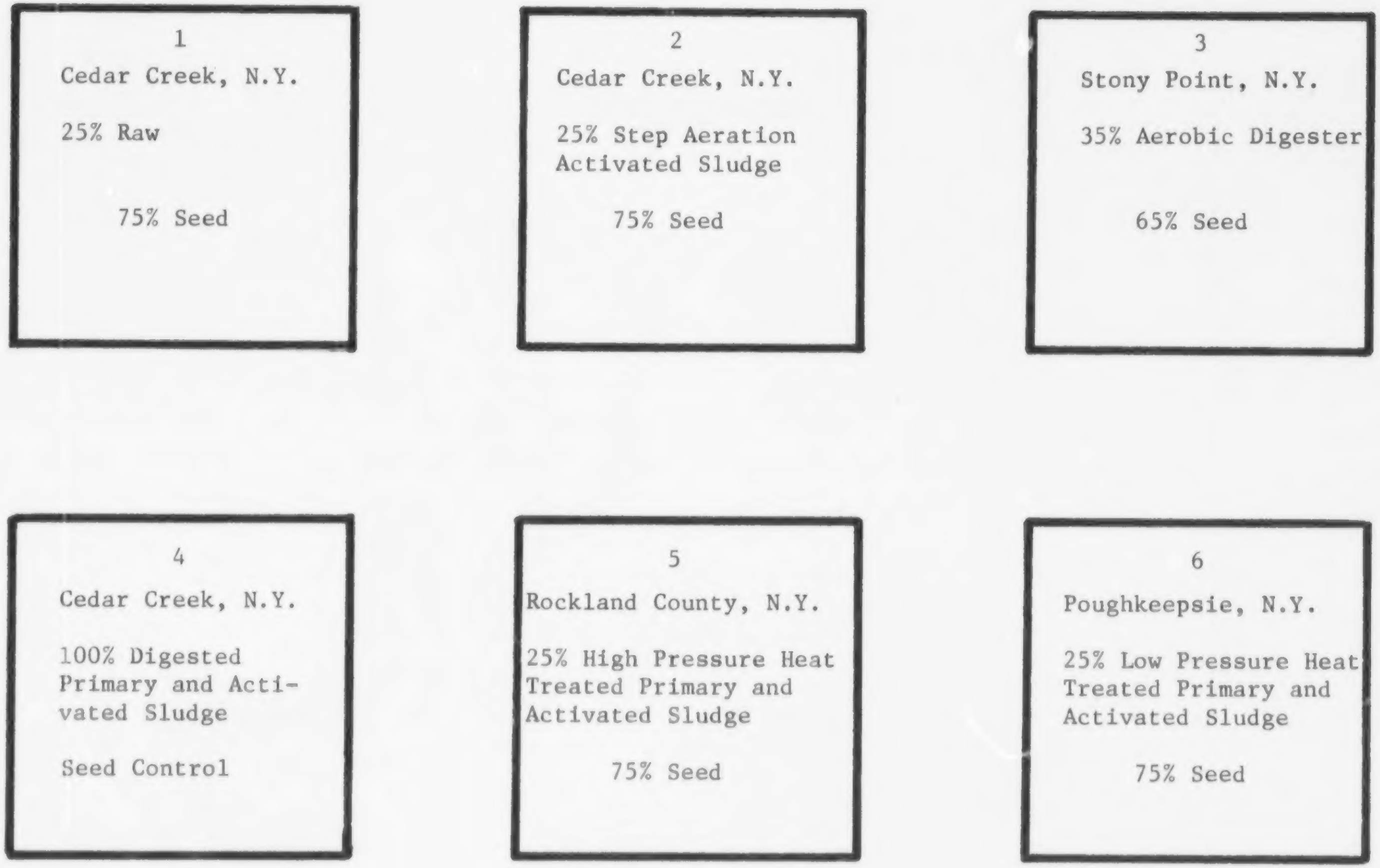

1
Cedar Creek, N.Y.
25% Raw
75% Seed
2
Cedar Creek, N.Y.
25% Step Aeration Activated Sludge
75% Seed
3
Stony Point, N.Y.
35% Aerobic Digester
65% Seed
4
Cedar Creek, N.Y.
100% Digested Primary and Activated Sludge
Seed Control
5
Rockland County, N.Y.
25% High Pressure Heat Treated Primary and Activated Sludge
75% Seed
6
Poughkeepsie, N.Y.
25% Low Pressure Heat Treated Primary and Activated Sludge
75% Seed

Figure 61. Phase I. Anaerobic Reactor Contents

1A
Beacon, N.Y.

6 Days Digestion

2A
Cold Spring, N.Y.

1.1 Days Aeration

3A
Musconetong, N.J.

21 Days Digestion

4A
Stony Point, N.Y.

14 Days Digestion

5A
Rockland County, N.Y.

16% High Pressure
Heat Treated Primary
and Activated Sludge

84% Stony Point Seed

6A
Poughkeepsie, N.Y.

1.6% Low Pressure
Heat Treated Primary
and Activated Sludge

98.4% Stony Point Seed

Figure 62. Phase I. Aerobic Reactor Contents

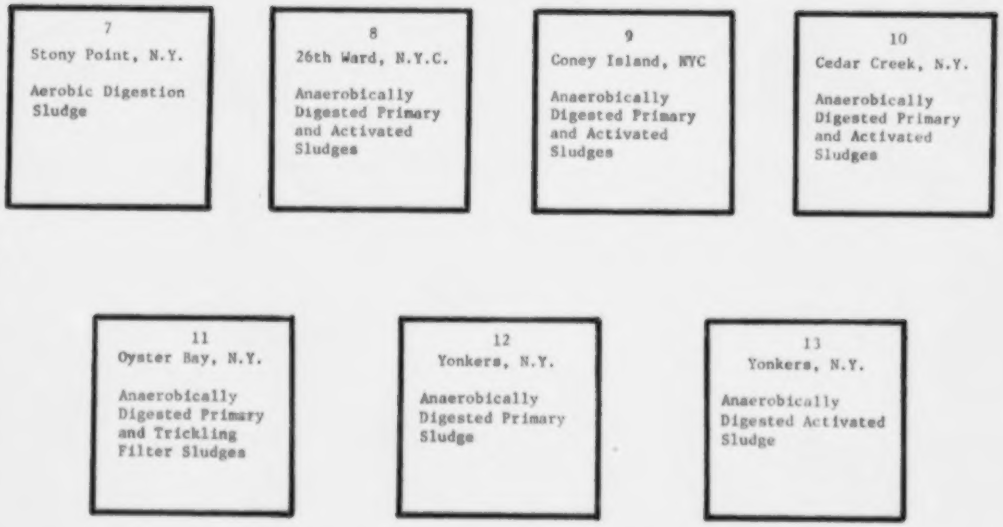

7
Stony Point, N.Y.
Aerobic Digestion Sludge
8
26th Ward, N.Y.C.
Anaerobically Digested Primary and Activated Sludges
9
Coney Island, NYC
Anaerobically Digested Primary and Activated Sludges
10
Cedar Creek, N.Y.
Anaerobically Digested Primary and Activated Sludges
11
Oyster Bay, N.Y.
Anaerobically Digested Primary and Trickling Filter Sludges
12
Yonkers, N.Y.
Anaerobically Digested Primary Sludge
13
Yonkers, N.Y.
Anaerobically Digested Activated Sludge

Figure 63. Phase II. Anaerobic Reactor Contents

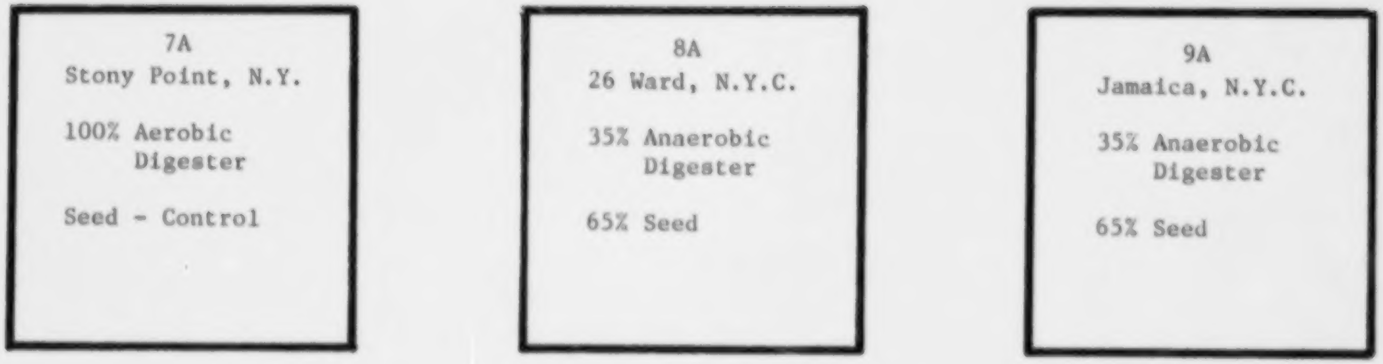

7A
Stony Point, N.Y.
100% Aerobic Digester
Seed - Control
8A
26 Ward, N.Y.C.
35% Anaerobic Digester
65% Seed
9A
Jamaica, N.Y.C.
35% Anaerobic Digester
65% Seed

Figure 64. Phase II. Aerobic Reactor Contents

Start-up of Reactors

Anaerobically digested primary and activated sludges from the Nassau County, New York, Cedar Creek plant was used as seed in the Phase I anaerobic digestion experiments. Reactor 4 contained 100% Cedar Creek sludge, and was used as the seed control. The remaining five reactors contained different amounts of Cedar Creek seed and an amount of the sludge under investigation (Figure 61). The reactors were maintained at a temperature of 35±°C, and were completely mixed throughout the course of the experiments. The volume of the reactors was initially 18ℓ, but declined in volume as samples for analysis were removed.

Phase I aerobic digestion experiments continued the aeration of sludges obtained from three aerobic digestion plants. A sample from the Cold Spring, New York extended aeration process was also further digested aerobically.

Sludge from Stony Point, N.Y. was digested in Reactor 4A and was also used as seed. Different thermal treatment sludges were mixed with Stony Point seed to form reactors 5A and 6A (Figure 62). These reactors were operated at room temperature and completely mixed by diffused air aeration. The initial volume of the reactors was 18ℓ.

All Phase II anaerobic reactors contained anaerobic sludges except reactor 7 which contained Stony Point aerobic digestion sludge. (Figure 63)

Phase II aerobic reactors were also seeded with Stony Point sludge. Reactor 7A was the seed control while reactors 8A and 9A contained mixtures of the seed and anaerobic sludges (Figure 64).

Before sealing, the anaerobic reactors were purged with nitrogen gas. Mixing was initiated one day after set-up to assure no oxygen was present. No special precautions were made in the set-up of the aerobic units.

SECTION 7

LABORATORY RESULTS

AEROBIC DIGESTION

Sludges from four different aerobic treatment plants were analyzed during the course of the study. The sources of the sludges were Beacon, New York, Musconetcong, New Jersey, Cold Spring and Stony Point, New York. Sludges studied are shown in Figures 62 and 64. Aerobic digestion of anaerobic sludge and thermally treated sludge was conducted in our laboratory using Stony Point sludge as seed. Tables 39 and 40 give the zero and sixty day results and the number of days required for the various parameters to reach equilibrium.

Pure Sludges

Analysis of data obtained with pure sludges was simple in contrast to the case of sludges mixed with seed sludge where evaluation of effects requires comparison with the behavior of the seed sludge. Some data are tabularized to facilitate comparisons. Most data are presented in graphical form so that trends may be easily observed. In order to minimize the number of plots required, several parameters are plotted together. The scales frequently are different and the technique used is to use a scale multiplication factor(s) after the parameter. As an example in Figure 65a for %TS, the scale must be multiplied by 10^{-1} or 0.1; thus the zero day %TS (Total Solids) is 0.44.

Beacon, New York (Reactor 1A)

Results of tests performed sludge from the aerobic digester at the Beacon, New York wastewater facility are shown in Figures 65 and 66. Total solids, volatile solids, suspended solids, and volatile suspended solids all show a downward trend and approach equilibrium in approximately 40 days as seen in Figure 65a. Solids reduction may typically be characterized by an initial rapid decrease in concentration followed by a slowly leveling trend. The curves for all these solids, tend to parallel each other. A similar downward trend leveling off in about 20 days may be seen for BOD_5 is more sensitive than COD when trying to identify stability as BOD reduction was about 75% whereas COD reduction was 25% in the 20 day period. It may also be seen in Figure 65b that the curve for specific oxygen uptake rate (SOUR) resembles the curve for BOD_5. The SOUR approaches a steady state value of about 1.2 mg O_2/gm VSS-hr.

The plot of alkalinity in Figure 63c shows a rapid decrease from 430 mg/ℓ to 20 mg/ℓ in about 20 days. It is also of interest to note the relationship between pH and conductivity. The two curves approximate mirror images of each other, but the minimum and maximum points are displaced by about 10 days.

Figure 65d illustrates the relationship between organic and ammonia nitrogen. The organic nitrogen concentration declines rapidly over the first

20 days, and then levels off. Initially we see a conversion of organic nitrogen to ammonia nitrogen as seen in Figure 65d. As the concentration of organic nitrogen decreases, we see a corresponding increase in ammonia nitrogen concentration. As the organic nitrogen concentration reaches equilibrium, we see the ammonia nitrogen concentration decline and eventually achieve equilibrium. This ammonia nitrogen peak occurred about 17 days into the experiment. It is important to note the different scales used for these two parameters in the Figure 65b.

The filterability of this sludge did not change much during the first 34 days of the experiment. The capillary suction time (CST) was relatively constant at about 12 seconds. No significant change in specific resistance was observed. Values averaged about 9.5×10^{13} m/kg in Figure 66a. Grease and oil was measured three times for the Beacon sludge. These points plotted in Figure 66b show that percent grease decreased from about 18 to 6.5 percent, a reduction of 64%, in approximately 28 days.

Cold Spring, New York (Reactor 2A)

Figures 66 and 67 show the data collected during our study on sludge from the Cold Spring, New York extended aeration process. All forms of solids measurement, percent total, percent volatile, suspended, and volatile suspended solids all yielded a decreasing trend which slowly leveled off as illustrated in Figure 67a. Figure 67b shows that BOD_5 is again a much more senstive indicator of sludge stability than COD. It is of interest to note that the curve for SOUR exhibits a relatively gentle decreasing slope from the beginning of the study reaching a steady state value of 0.6 mgO_2/gm VSS-hr.

Figure 67c shows a relationship between pH and conductivity. Decreases in pH correspond closely to increases in conductivity and vice versa. A rapid drop in alkalinity is observed over the first 20 days decreasing from 200 to 30 mg/ℓ as given in Figure 67c. Ammonia and organic nitrogen are plotted in Figure 67c. The initial and final concentration of ammonia nitrogen is about 1.0 mg/ℓ but on day 27 an ammonia peak of 26 mg/ℓ is reached. Organic nitrogen drops rapidly during the first 20 days from 290 to 160 mg/ℓ.

Parameters measuring filterability are shown in Figure 66c. The capillary suction time remains constant at about 5 seconds during the first 49 days of the study. During this same period the specific resistance remains constant at about 1.4×10^{12} m/kg. Figure 69b shows the grease and oil concentration declining. Although only three points are reported for grease and oil, these points strongly suggest a downward trend.

Musconetcong, New Jersey (Reactor 3A)

Sludge taken from the aerobic digester at Musconetcong, New Jersey was further digested in our laboratory, and results are presented in Figures 68 and 69. Data for solids indicates a trend where concentration decreases rapidly initially, and then levels off. Data indicates that solids concentration, both total and volatile, is reduced by approximately one half in 50 days. After 50 days, the sludge is resistant to further biodegradation concentration. This plot is typical of what was obtained seen in the other aerobic reactors.

Figure 68b shows the relationship between BOD_5, COD, and SOUR. The curve for BOD_5 shows a decrease from 3300 mg/ℓ to about 100 mg/ℓ in 40 days. The COD curve shows a similar trend decreasing from 18000 to 500 mg/ℓ in 50 days. BOD_5, COD and SOUR attain equilibrium between 20 to 30 days. A decrease in SOUR from 3.6 to 0.4 mgO_2/gm VSS-hr is given in Figure 68b.

No relationship is apparent between conductivity and pH as can be seen from Figure 68c. The figure also shows a drop in alkalinity from 600 to zero mg/ℓ in about 40 days. If the data point collected on day 44 were erroneous, the peak in the conductivity curve would be eliminated and the three curves would correspond better.

Figure 68d illustrates the relationship between organic and ammonia nitrogen. The initial and final concentration of ammonia nitrogen is about 10 mg/ℓ. On day 22 a peak in ammonia nitrogen of 90 mg/ℓ was observed. Organic nitrogen has an initial concentration at 680 mg/ℓ and levels off to 200 mg/ℓ in approximately 60 days. Figure 69a shows a very slight increase in CST and specific resistance during this same period. Figure 69b indicates a markedly decreasing trend for grease and oil. This is typical of what was observed for the previous reactors.

Stony Point, New York (Reactor 4A)

This reactor was established using sludge taken from the Stony Point treatment plant during the summer. The data from this reactor was also used as a seed correction for the thermally treated sludges undergoing aerobic digestion.

Solids data indicate a decreasing trend followed by leveling off in 20 to 30 days as shown in Figure 70a. This trend in data is similar to trends seen in the previous reactors. Although the trends are similar, the value at which the various solids parameters reach equilibrium may vary with the parameter and the reactor. In general, suspended and volatile suspended solids seem to be more sensitive by exhibiting greater rates of change and approach steady state sooner than do the corresponding total solids.

Figure 70b shows the relationship between BOD_5, COD and SOUR. COD declines from 5600 to 3000 mg/ℓ in about 30 days. BOD_5 and SOUR curves are similar to those discussed previously. The SOUR reaches an equilibrium value of approximately 0.8 mgO_2/gm-VSS-hr. Again, pH and conductivity are as mirror images of each other as shown in Figure 70c. Data from Beacon and Cold Spring behaved in a similar fashion. Alkalinity declined to a value of zero in approximately 20 days. Figure 70d shows a peak in ammonia nitrogen occurring on day nine. Correspondingly organic nitrogen decreased from 330 to 100 mg/ℓ in approximately 30 days. Figure 69c shows the capillary suction time and specific resistance of this sludge remaining constant at approximately 10 seconds and 1.7 x 10^{13} m/dg, respectively, throughout the course of our study. A decreasing trend for grease and oil is shown in Figure 69d.

Stony Point, New York (Reactor 7A)

Sludge taken from the Stony Point aerobic digester during the winter was used as seed in experiments evaluating the aerobic digestibility of anaerobic sludges. Small variations exist between this sludge and Stony Point sludge taken during the summer. Although the COD of the winter sludge is higher, BOD_5 concentrations of the summer sludge are more than twice the concentration encountered in the winter Stony Point sludge. The SOUR for the summer sludge was about 3 times that of the winter sludge. The summer Stony Point sludge appears to be more active biologically than the winter sludge, even though both were aerobically digested at room temperature. Figure 71a shows the trends that the solids follow. When compared to the summer sludge reactor (Figure 70a), the curves for the winter sludge show smaller removal rates, indicating a more stable sludge. More solids destruction occurred in the summer sludge than in the winter sludge. The SOUR rate was a constant 0.5 mgO_2/gm VSS-hr for the winter sludge throughout the course of the study as Figure 71b illustrates. Reductions in COD and BOD_5 are typical of the other aerobic sludges studied as can be seen in Figure 71b. The plot of conductivity shown in Figure 71c was constant at about 1600 uhmos/cm throughout the course of the experiment. The alkalinity of the winter sludge behaves similar to the summer sludge dropping sharply during the first 20 days. The pH of the summer sludge declines and then rises again. The pH of the winter sludge declines and then levels off as seen in Figure 71c. Comparison of Figures 71d and 70d show that ammonia and organic nitrogen in both Stony Point reactors behave in a similar fashion. Figure 72a shows specific resistance and CST of the sludge remained constant during the study. The CST shows no real trend. The specific resistance of the winter Stony Point sludge is higher than the summer sludge. Grease and oil concentration can be seen decreasing from 9.6 to 1.9 mg/ℓ. This is typical when compared to the other aerobic sludges studied.

Mixtures with Thermally Treated Sludges

Sludges from the wet oxidation processes at Rockland County, New York and Poughkeepsie, New York were used in this part of the study. Sludge taken from the Stony Point plant during the summer was used as seed in the reactors. One reactor consisted of 16 percent by volume Rockland County heat treated sludge in Stony Point seed. The other reactor was 1.6 percent by volume Poughkeepsie heat treated sludge in Stony Point seed.

Rockland County, New York (Reactor 5A)

Since the wet oxidation process tends to concentrate sludges, the initial concentrations of this reactor are higher than those found in reactors containing aerobic sludges. Typically, percent total solids, suspended solids and volatile suspended solids are found to be higher in concentration in the thermally treated sludges. Figure 73a shows that although percent total solids, suspended solids, and volatile suspended solids are higher, percent volatile solids is less than percentages found in pure aerobic sludge reactors. This is due to oxidation of much of the volatile material in the sludge during the wet oxidation process. Although little change is observed in the SOUR rate as shown in Figure 73b, BOD_5 and COD are quite responsive to aerobic digestion. The curves for BOD_5 and COD level off in approximately 20 days. The BOD_5 concentration of this reactor is typical of concentrations found in the pure sludge reactors, however, the COD concentration is much higher than concentrations found in the pure anaerobic sludge reactors as given in Table 39.

Pure aerobic sludges studied in the laboratory exhibit an initial drop in pH followed by an increase and leveling off trend. The mixture of sludge from the Rockland County and Stony Point plants shows an initial increase in pH followed by a decrease and eventual leveling off as can be seen in Figure 73c. Figure 73c shows conductivity decreasing slowly. This is not typical of what was observed for pure aerobic sludges which increased in conductivity initially then a decrease and eventually leveled off. A decreasing alkalinity trend, which at the end of the run approached zero, is typical of what was observed for pure aerobic sludge reactors. The reactor containing the Rockland County thermal sludge approached an equilibrium alkalinity concentration of approximately 340 mg/ℓ.

Both ammonia and organic nitrogen followed trends typical of the pure aerobic sludges. The ammonia nitrogen reached a peak value of 85 mg/ℓ in approximately 15 days. Although the initial organic nitrogen concentration was higher, the equilibrium concentration of organic nitrogen was similar to concentrations encountered for pure aerobic sludges. Filterability seems to improve slightly as indicated in Figure 74a. Figure 74a shows that specific resistance declined, while CST remained constant. Figure 74b shows grease and oil decreasing which was the typical trend observed for pure aerobic sludges.

Poughkeepsie, New York (Reactor 6A)

Figure 75a illustrates the degradation of solids in the reactor containing 1.6 percent Poughkeepsie heat treated sludge and 98.4% Stony Point aerobic sludge. No major differences exist between the reduction of solids in this reactor, and the reduction encountered in the pure aerobic sludge reactors. Both BOD_5 and COD concentrations drop off rapidly, and level off in approximately 40 days. Little change is observed in the SOUR. The seed sludge had an initial SOUR of approximately 2.1 mgO_2/gm VSS-hr. Since the seed SOUR is higher than the SOUR in the Poughkeepsie reactor, toxicity might be suspected or it could be affected by the dilution. The higher volatile suspended solids concentration which was inactivated by the heat treatment is also in part responsible for the lower SOUR. Figure 75c shows conductivity declining whereas pure aerobic sludges tend to have increasing conductivity values. The pH of the Poughkeepsie reactor shows a sharp increase initially although the pH declines to the original value before rising slowly again.

Alkalinity also declined rapidly during the first 20 days but remained at steady state. This trend is similar to that observed for pure aerobic sludges. Organic and ammonia nitrogen concentrations behave in a fashion similar to what was observed for pure aerobic sludges although ammonia nitrogen did not reach a sharp peak as shown in Figure 75d. All other aerobic units discussed previously showed sharp ammonia nitrogen peaks. Figure 74c shows the CST to be fairly constant while the specific resistance of this sludge rose slightly. A curve indicating a decreasing concentration of grease and oil is given in Figure 74b and is typical of what was observed in reactors containing pure aerobic sludges.

Aerobic Digestion of Anaerobically Digested Sludges

In this part of the research study, sludges from anaerobic digesters were mixed with aerobic sludge and aerobically digested. Anaerobic sludges were taken from the New York City 26th Ward and Jamaica treatment plants. 26th Ward sludge was used in this portion of the study was identical to the sludge used in the anaerobic digestion study. The reactors were seeded using Stony Point winter aerobic sludge. Each of the reactors contained 34 percent anaerobic sludge and 65 percent Stony Point sludge.

26th Ward Mixture (Reactor 8A)

The addition of anaerobic sludge to the aerobic sludge created, upon aeration, a more concentrated aerobic sludge. This reactor consisted of 35 percent 26th Ward anaerobic sludge and 65 percent Stony Point aerobic sludge. Comparison of the pure Stony Point seed and this sludge mixture may be made using Table 40. The 26th Ward mixture has higher concentrations of suspended solids, volatile suspended solids, as well as percent total solids. When compared to the Stony Point seed percent volatile solids is about the same for both the 26th Ward mixture and Stony Point. Figure 76a shows the behavior of solids throughout the study. A comparison of Figures 76a and 71a shows that the percentage change in total and volatile solids of 26th Ward sludge and Stony Point sludge are about the same. Figure 76b shows the SOUR of the 26th Ward mixture dropping from about 2.0 to 0.3 mgO_2/gmVSS-hr whereas the Stony Point seed had a fairly stable SOUR of 0.4 mgO_2/gmVSS-hr as shown in Figure 71b. The COD concentration of the 26th Ward mixture is reduced much like the COD concentration of the seed, although the 26th Ward mixture has higher concentrations. COD and BOD_5 reduction can be observed in Figure 76b. The BOD_5 reduction of the 26th Ward sludge is more rapid than the seed.

The BOD_5 decreased from 1300 to 150 mg/ℓ in 25 days. Although the seed shows a slight increase in conductivity, the 26th Ward mixture shows a significant increase in conductivity after 40 days. The pH of 26th Ward mixture decreased from 8 to 4.2 as shown in Figure 76c while the pH of the seed declined close to one unit during the course of the experiment. Figure 76 shows alkalinity of the 26th Ward mixture dropping from 1600 to 0 mg/ℓ in less than 30 days. During this same period, the Stony Point seed alkalinity drops from 40 to 8 mg/ℓ.

Data from pure aeration of aerobic sludges showed an ammonia nitrogen peak during the first two weeks of each study. Ammonia nitrogen of the 26th Ward mixture decreased from 315 mg/ℓ to almost zero in less than 50 days as can be seen in Figure 76d. Although a peak concentration of 200 mg/ℓ occurs in the Stony Point seed, the 26th Ward mixture shows a steadily declining trend. Figure 76d shows a decreasing organic nitrogen trend similar to the Stony Point seed, and typical of what was observed in the pure aerobic sludge reactors. Specific resistance and capillary suction time remain relatively constant throughout the study for the 26th Ward mixture. Values for specific resistance and capillary suction time are higher for the 26th Ward mixture in comparison to values for the Stony Point seed. Figure 77b shows grease and oil concentrations also decreasing. In general, the trends in changes in concentration were similar in the anaerobic sludges mixed with seed and the pure aerobic sludges, except that the concentrations were frequently much higher in the anaerobic sludges.

Jamaica Mixture (Reactor 9A)

A mixture was made using 35% Jamaica, New York anaerobic sludge and 65% Stony Point aerobic sludge. This Jamaica mixture was aerobically digested and results are presented in Figures 78 and 79. Percent total solids, suspended solids, and volatile suspended show an initial decreasing trend and approach equilibrium concentrations in approximately 30 days. Reduction in percent volatile solids seems to follow a straight line decreasing trend as can be observed in Figure 78a. Percent volatile solids does not seem to be approaching any equilibrium value, but is only decreasing at a rate of about 6% in 80 days. Initially, the SOUR of this sludge was 1.8 mgO_2/gmVSS-hr and equilibrium was reached in approximately 15 days when the SOUR levels off at 0.4 mgO_2/gmVSS-hr. as shown in Figure 78b. Both the BOD and COD decreased very rapidly in the first 30 days of the aeration process and achieved a steady state condition.

Figure 78c shows a major decline in pH from 8.0 to 5.2 in approximately 25 days. During this same period we see a similar significant decrease in alkalinity from 1250 to 50 mg/ℓ. Conductivity remained constant for close to 45 days then rose slightly. Figure 78d shows the organic nitrogen concentration remaining relatively constant throughout the study. The ammonia nitrogen concentration was higher than typical concentrations encountered in pure aerobic sludges. The ammonia nitrogen concentration decreased from 250 to 3 mg/ℓ in about 60 days.

The filterability of this sludge appears to deteriorate with increasing digestion time. The capillary suction time increased with further digestion as can be seen in Figure 79a. After 60 days digestion, specific resistance of the sludge also increased. A steady decrease in grease and oil concentration is clearly evident in Figure 79b. Percent grease and oil decreased from nine percent to less than two percent in 55 days. Figure 79c shows an increase in nitrates accompanied by a decrease in total nitrogen concentration. In approximately 60 days, both parameters achieve equilibrium concentrations.

TABLE 39. SUMMARY OF PARAMETERS - AEROBIC DIGESTION

Parameter	Beacon 1A			Cold Springs 2A			Musconetcong 3A			Stony Pt. 4A			Rockland 5A			Poughkeepsie 6A		
	Day 0	Day 60	Days to Equ.*	Day 0	Day 60	Days to Equ.	Day 0	Day 60	Days to Equ.	Day 0	Day 60	Days to Equ.	Day 0	Day 60	Days to Equ.	Day 0	Day 60	Days to Equ.
BODmg/ℓ	780	140	20	480	50	30	1600	40	40	350	40	35	3300	150	30	1000	100	50
COD,mg/ℓ	4000	1800	40	4700	3000	35	18000	5000	40	5600	2700	30	29000	10000	40	9400	5000	40
SOUR $\left(\frac{\text{mg } O_2}{\text{gmVS-hr}}\right)$	7.8	1.2	20	1.5	0.6	50	7.0	0.4	40	1.9	0.6	25	0.9	0.6	-	0.8	0.6	-
TS %	0.45	0.30	35	0.55	.40	-	1.3	0.7	50	0.70	0.47	30	2.4	1.5	20	1.1	0.7	40
VS %	76	62	35	65	63	-	70	59	50	60	50	30	50	40	50	60	51	45
SS,mg/ℓ	3600	2000	20	5200	3800	40	12000	7000	50	6400	4000	20	22000	15000	40	9600	6200	40
VSS,mg/ℓ	3000	1600	30	3600	2000	45	8000	4000	50	4000	2000	20	11000	8000	-	6000	3600	40
Conductiv. (umhos/cm)	900	1320	60	400	480	55	980	1800	50	1200	1400	60	2000	600	50	1240	1160	60
pH	6.8	5.6	45	6.1	6.0	50	6.4	4.0	40	5.4	5.1	40	5.6	7.0	50	5.4	5.4	40
Alk.mg/ℓ	430	20	20	200	30	30	600	0	40	240	0	20	800	360	50	520	40	20
NH_3-N mg/ℓ	10	10	40	1.0	1.0	40	6	30	80	8	2	25	10	10	70	4	4	60
Org-N mg/ℓ	470	80	25	290	140	35	680	140	60	330	90	30	980	100	50	480	140	60
CST,Sec	9	10	-	6	6	-	11	18	30	10.5	10.5	-	11	11	0	-	10	35
S.R.**	1200	1200	-	14	14	-	200	1250	30	190	170	-	170	100	-	50	110	-

*Equilibrium

**Specific Resistance $(m/kg)\times10^{11}$

TABLE 40. SUMMARY OF PARAMETERS - AEROBIC DIGESTION OF ANAEROBIC SLUDGES

Parameter	7A Stony Point(control) Day 0			8A 65% Stony Point + 35% 26 Ward Day 0			9A 65% Stony Point + 35% Jamaica Day 0		
	Day 0	Day 60	Days to Equil	Day 0	Day 60	Days to Equil	Day 0	Day 60	Days to Equil
BOD mg/ℓ	130	80	30	1,300	150	15	500	60	30
COD mg/ℓ	8,100	5,200	30	20,500	13,500	35	11,000	7,000	30
SOUR $\frac{\text{mg } O_2}{\text{gmVSS-hr}}$	0.4	0.4	0	2.0	0.5	35	1.8	0.4	25
% TS	0.88	0.72	30	1.75	1.50	25	1.04	0.87	25
% VS	61	57	-	60.0	53.0	40	62.0	57.0	-
SS mg/ℓ	7,100	5,300	40	16,000	13,000	40	9,200	6,500	25
VSS mg/ℓ	4,800	3,550	45	9,600	6,400	30	5,700	4,500	25
Conductivity umhos/cm	1,600	1,600	0	3,200	4,900	-	2,300	2,600	-
pH	5.5	4.8	10	8.0	4.1	40	8.0	5.2	35
Alk mg/ℓ	40	15	5	1,600	0	25	1,250	50	25
NH_3-N mg/ℓ	0	1	20	315	5	50	250	3	60
Org-N mg/ℓ	310	250	30	670	460	50	360	360	0
CST, sec	17	18	0	25	25	0	16	16	0
*Spec. Resistance	800	500	-	5,150	6,400	35	5,000	10,000	-
NO_3-N mg/ℓ	95	140	50	60	360	70	60	180	-
TKN mg/ℓ	320	290	35	1,005	485	60	620	350	50
TOTAL-N mg/ℓ	380	380	0	1,065	830	50	680	530	50

* Specific Resistance (m/kg) x 10^{11}

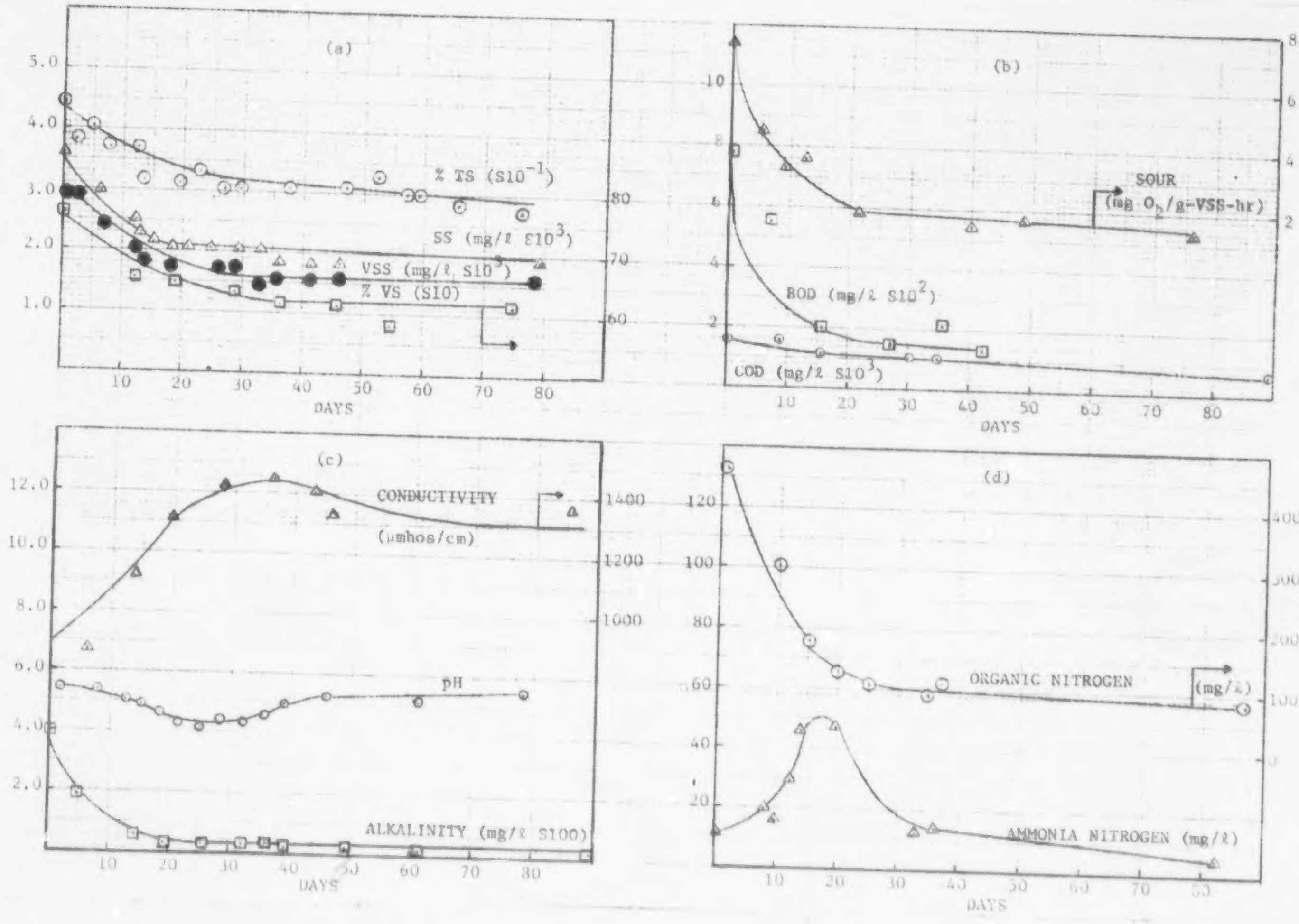
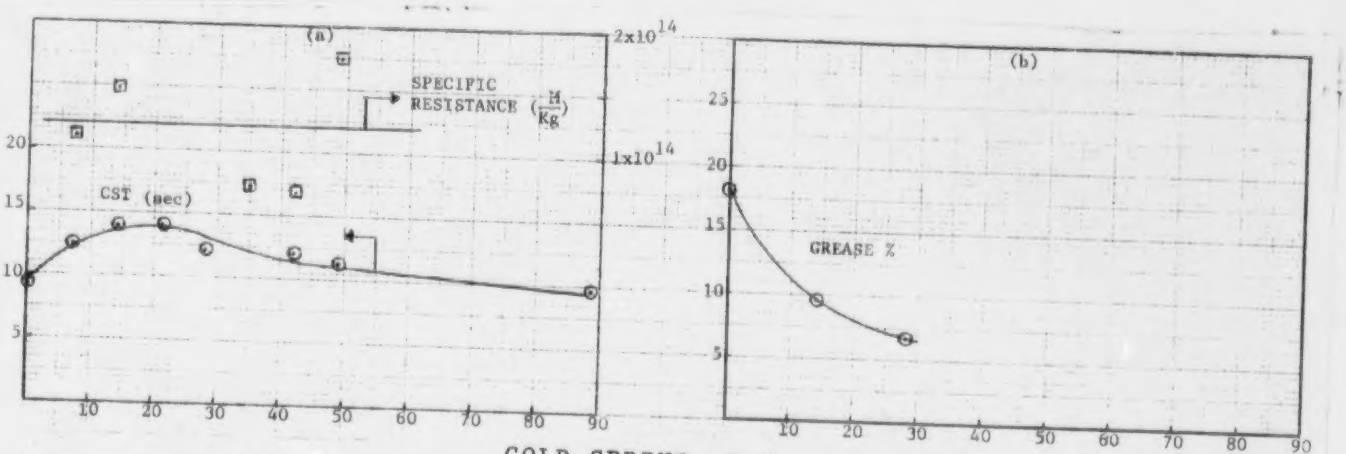


FIGURE 65. Beacon, N.Y. Anaerobic Sludge - Aerobic Stability Parameters

BEACON, N.Y.



COLD SPRING, N.Y.

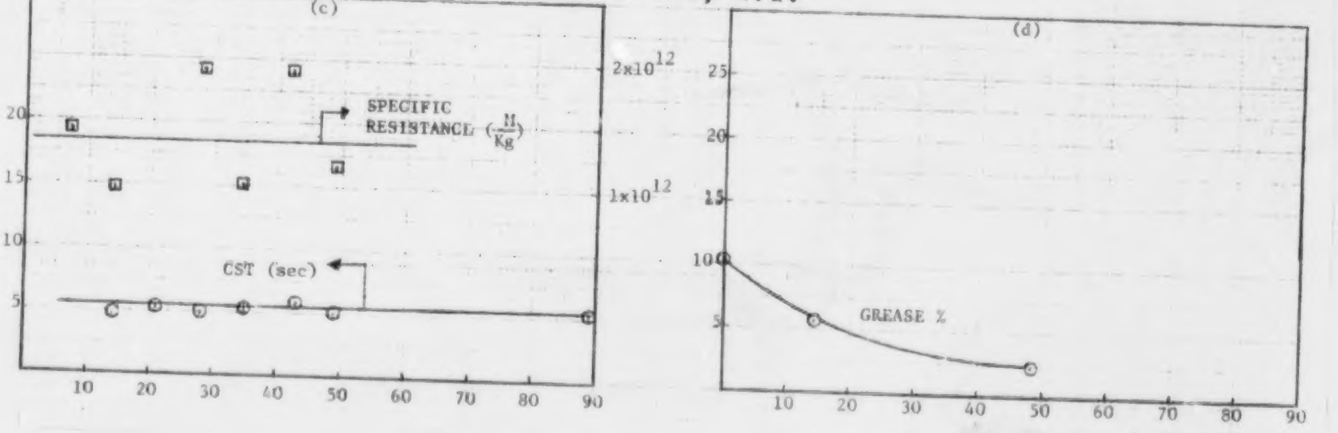


FIGURE 66. Beacon, N.Y. and Cold Spring, N.Y. Aerobic Sludges - Aerobic Stability Parameters

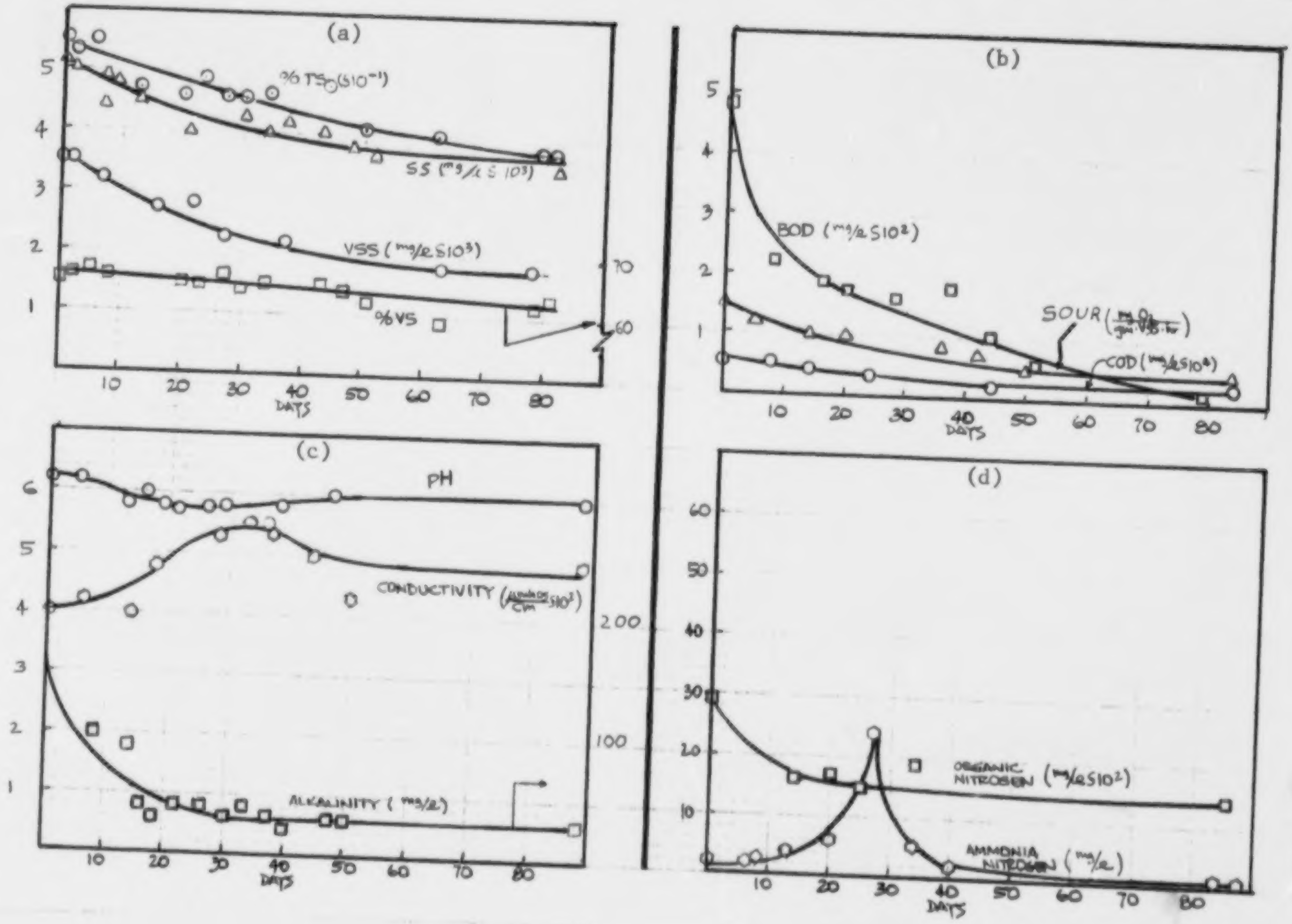


FIGURE 67. Cold Spring, N.Y. Aerobic Sludges - Aerobic Stability Parameters

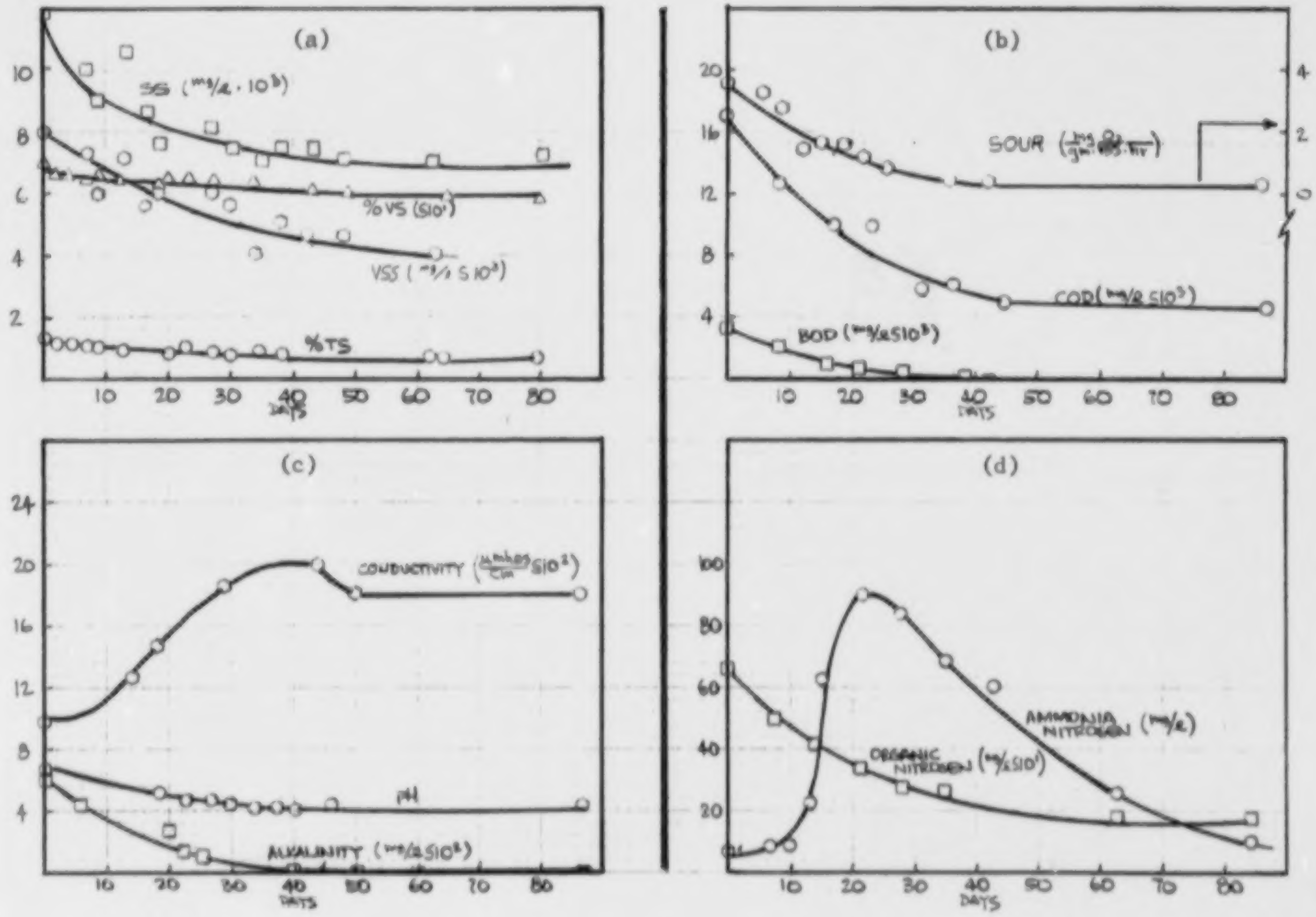


FIGURE 68. Musconetong, N.J. Aerobic Sludge - Aerobic Stability Parameters

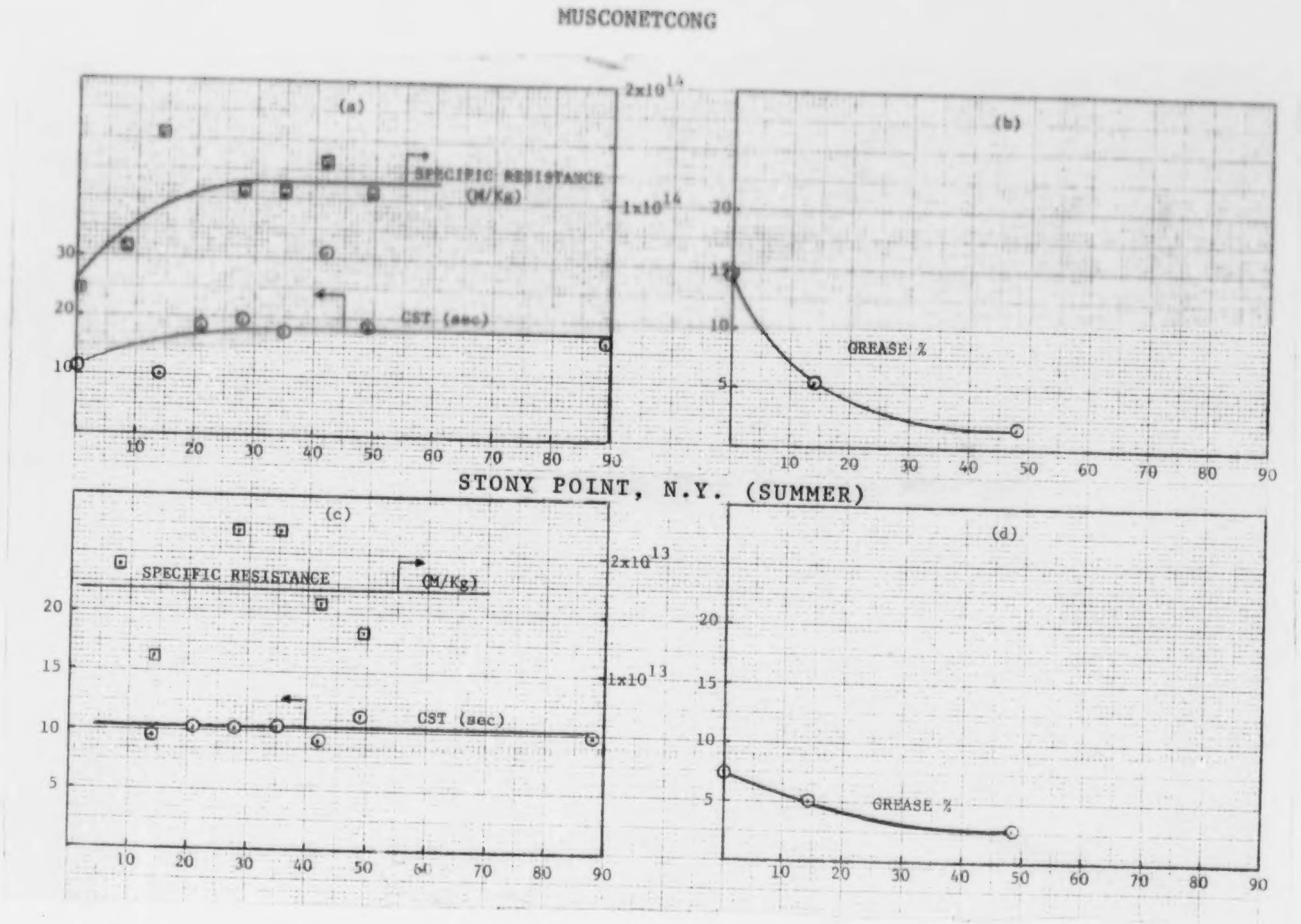


FIGURE 69. Musconetcong, N.J. and Stony Point, N.Y. Aerobic Sludges - Aerobic Stability Parameters

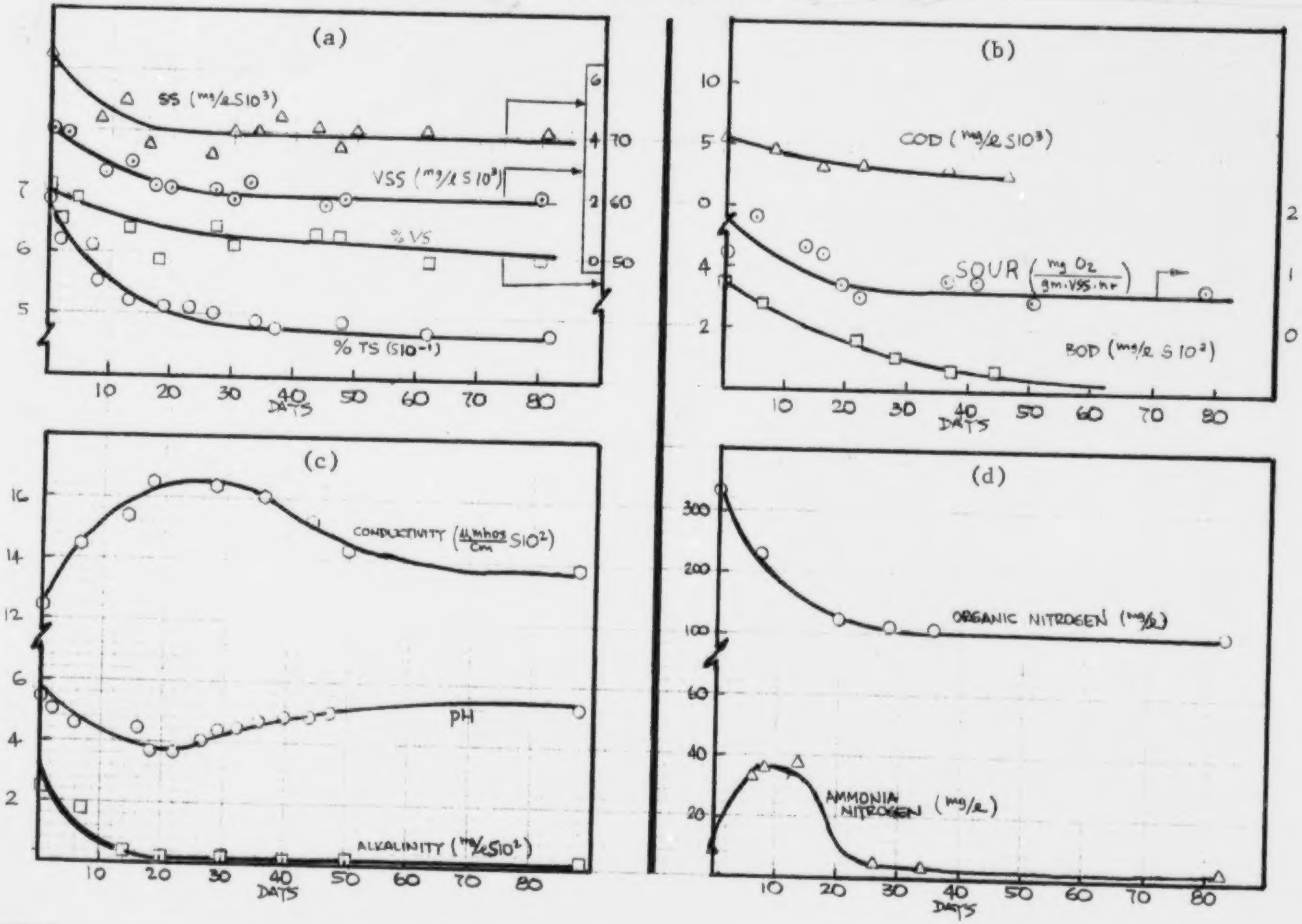


FIGURE 70. Stony Point, N.Y. (Summer) Aerobic Sludge - Aerobic Stability Parameters

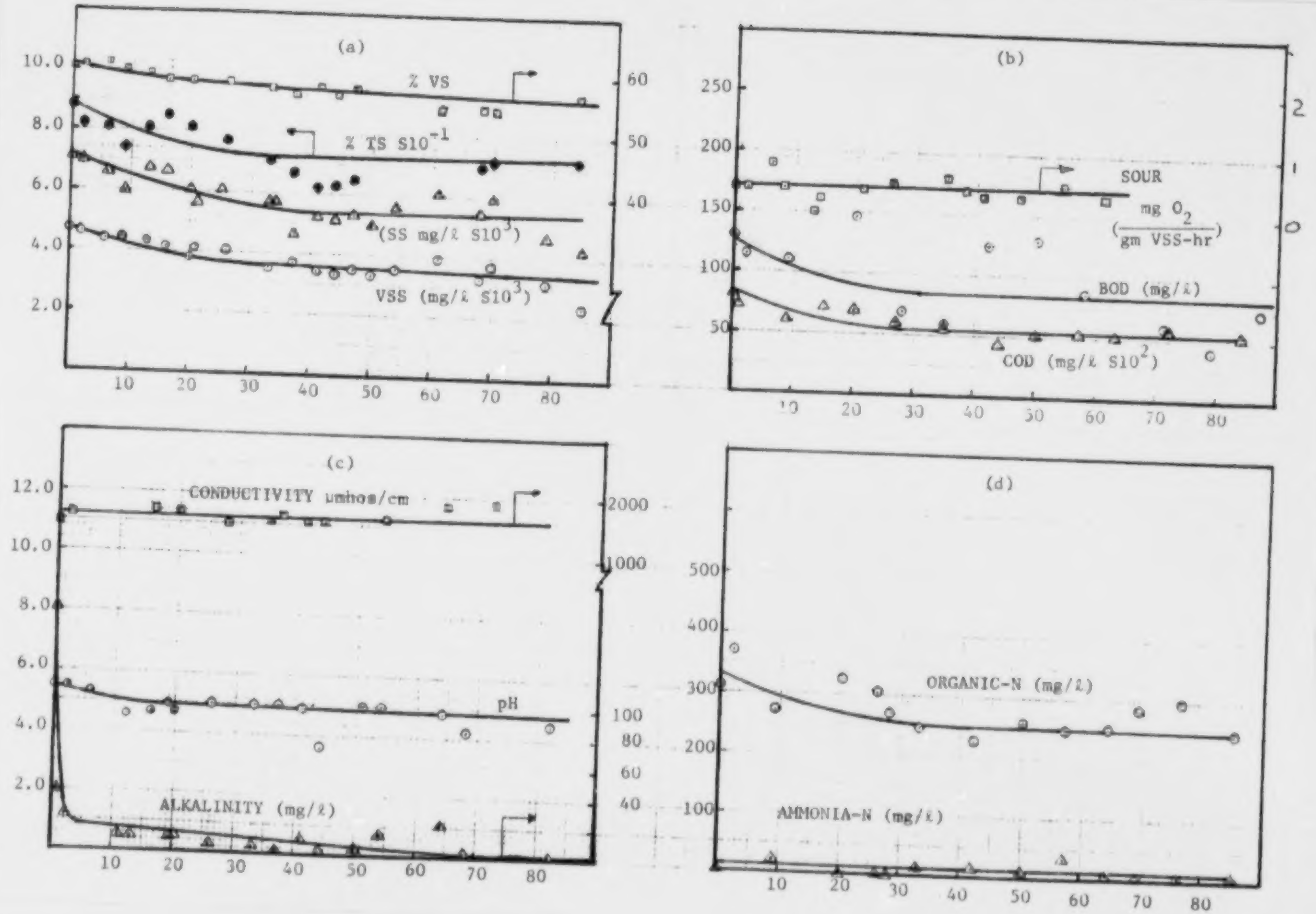


FIGURE 71. Stony Point, N.Y. (Winter) Aerobic Sludge - Aerobic Stability Parameters

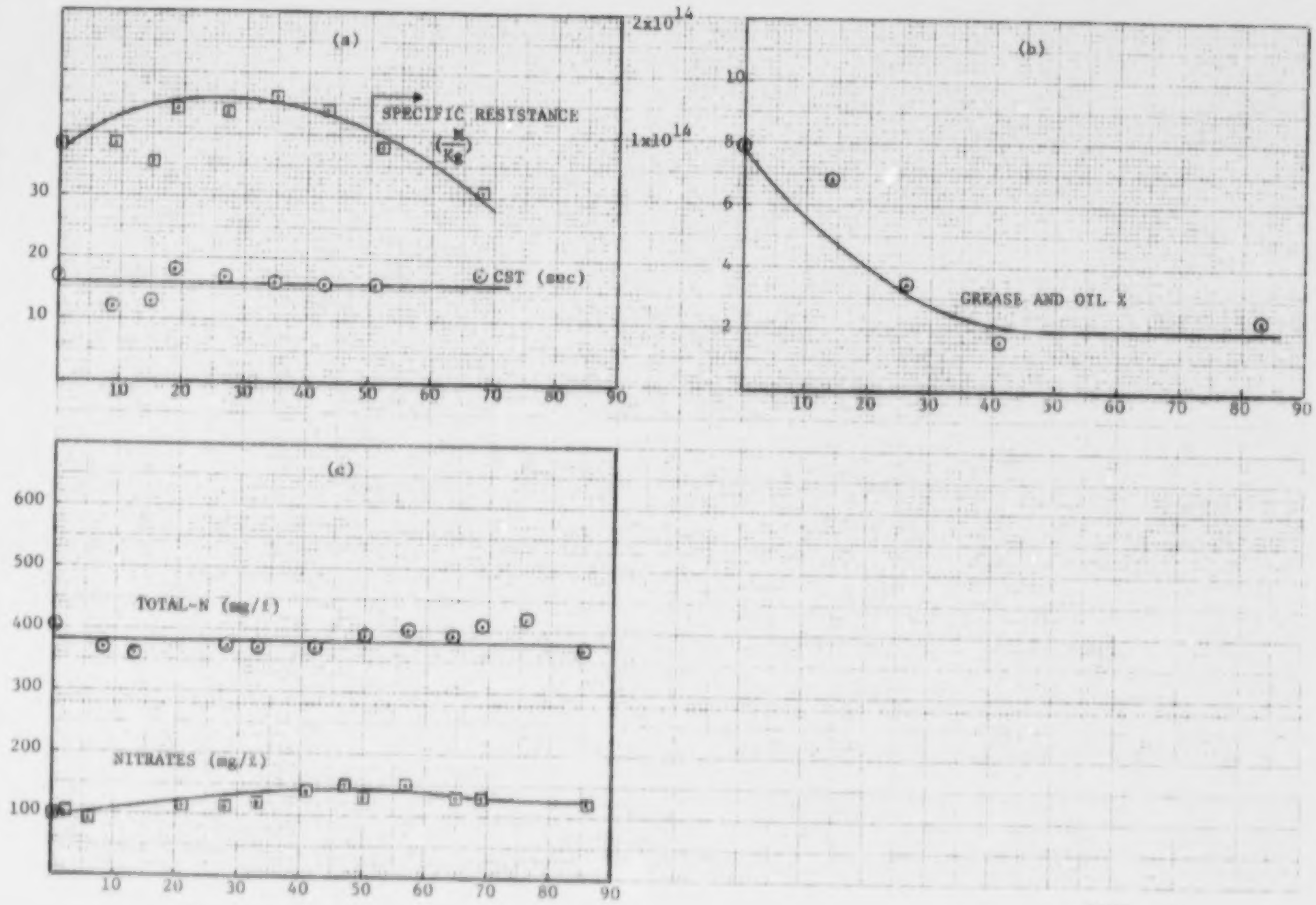


FIGURE 72. Stony Point, N.Y. (Winter) Aerobic Sludge - Additional Aerobic Stability Parameters

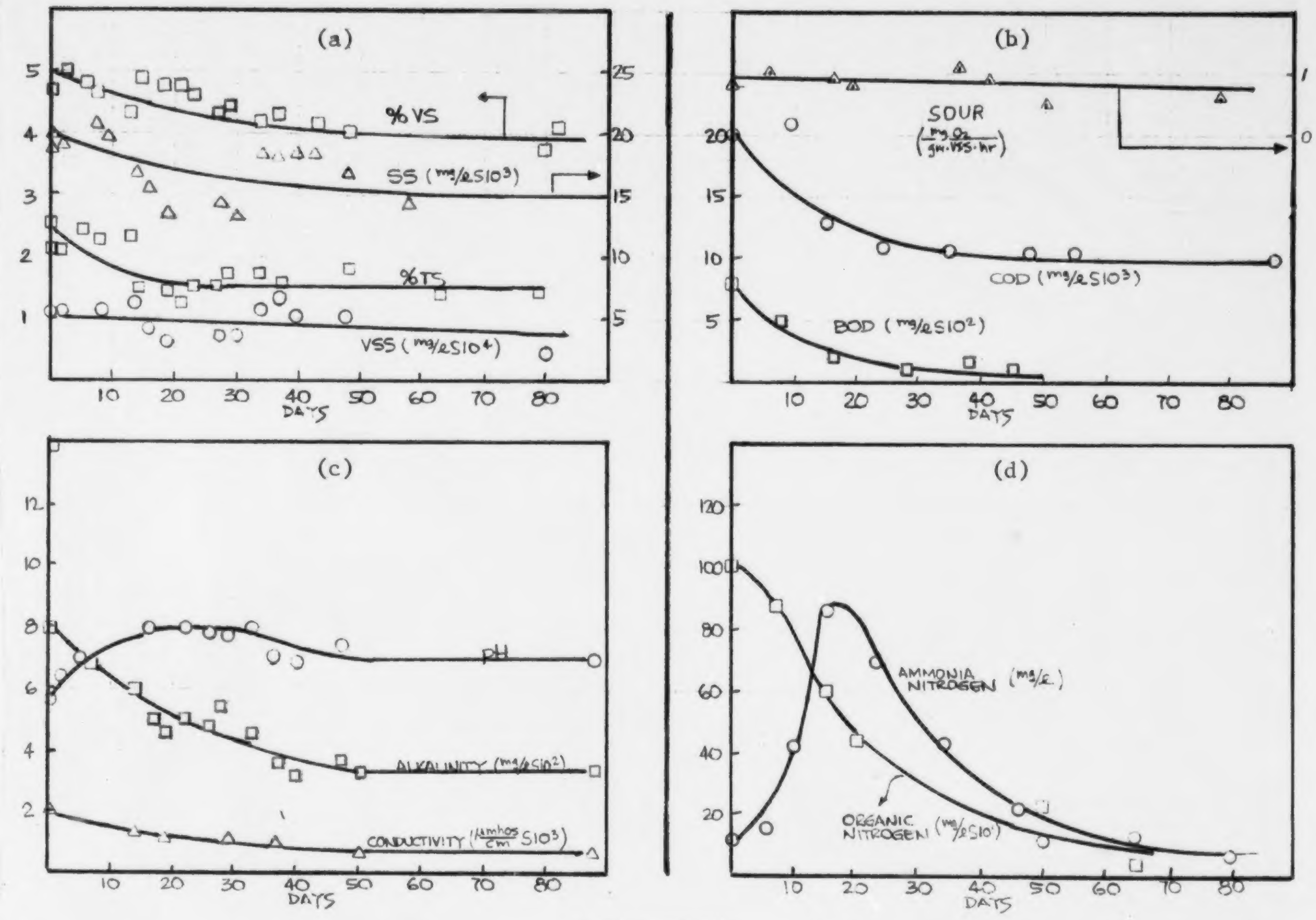
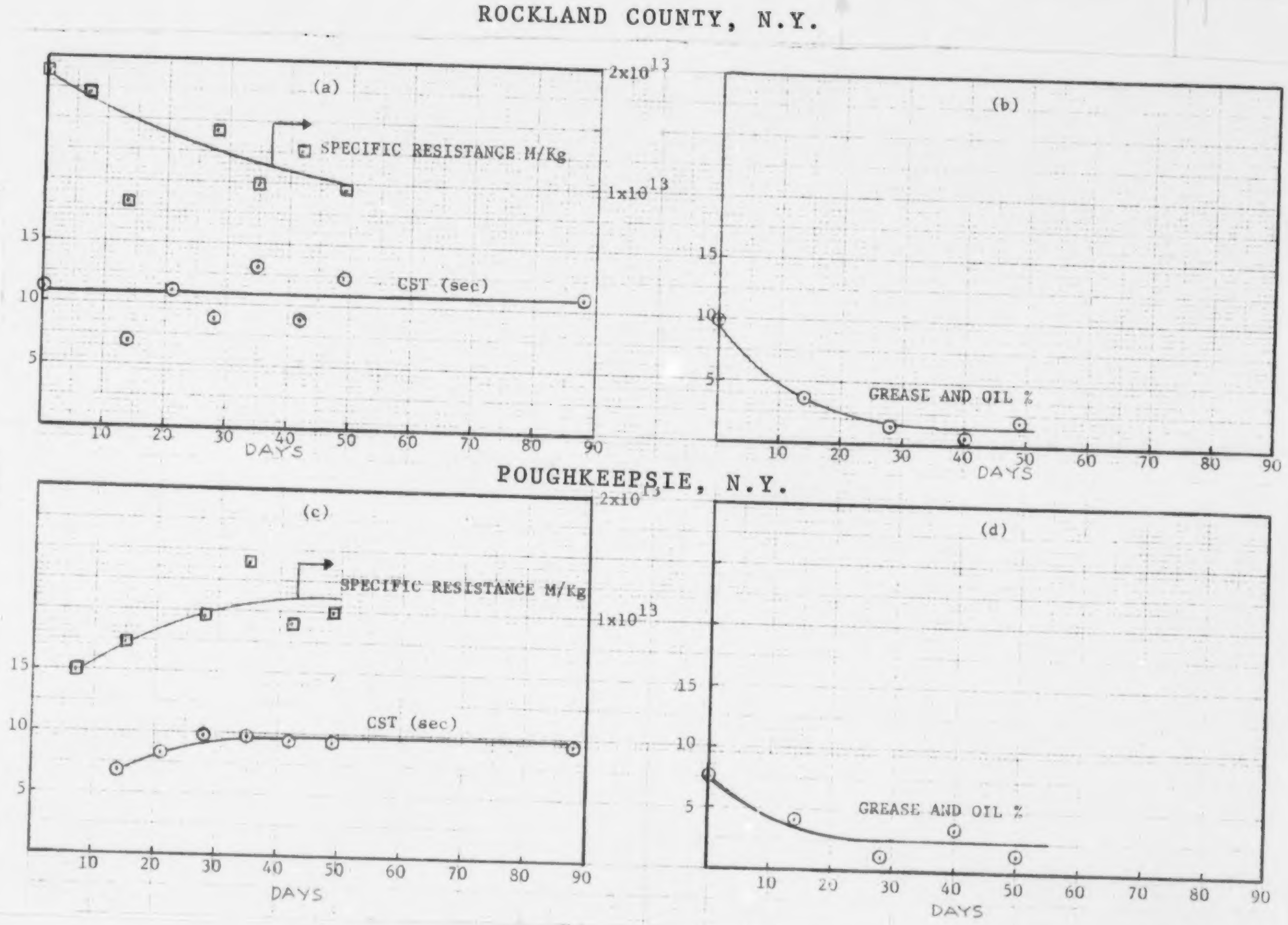


FIGURE 73. Rockland County, N.Y. Thermal Sludge - Aerobic Stability Parameters

EPA Form 2350-4 (4-80)
TYPING GUIDE SHEET

ROCKLAND COUNTY, N.Y.



POUGHKEEPSIE, N.Y.

FIGURE 74. Rockland County, N.Y. and Poughkeepsie, N.Y. Thermal Sludge - Aerobic Stability Parameters

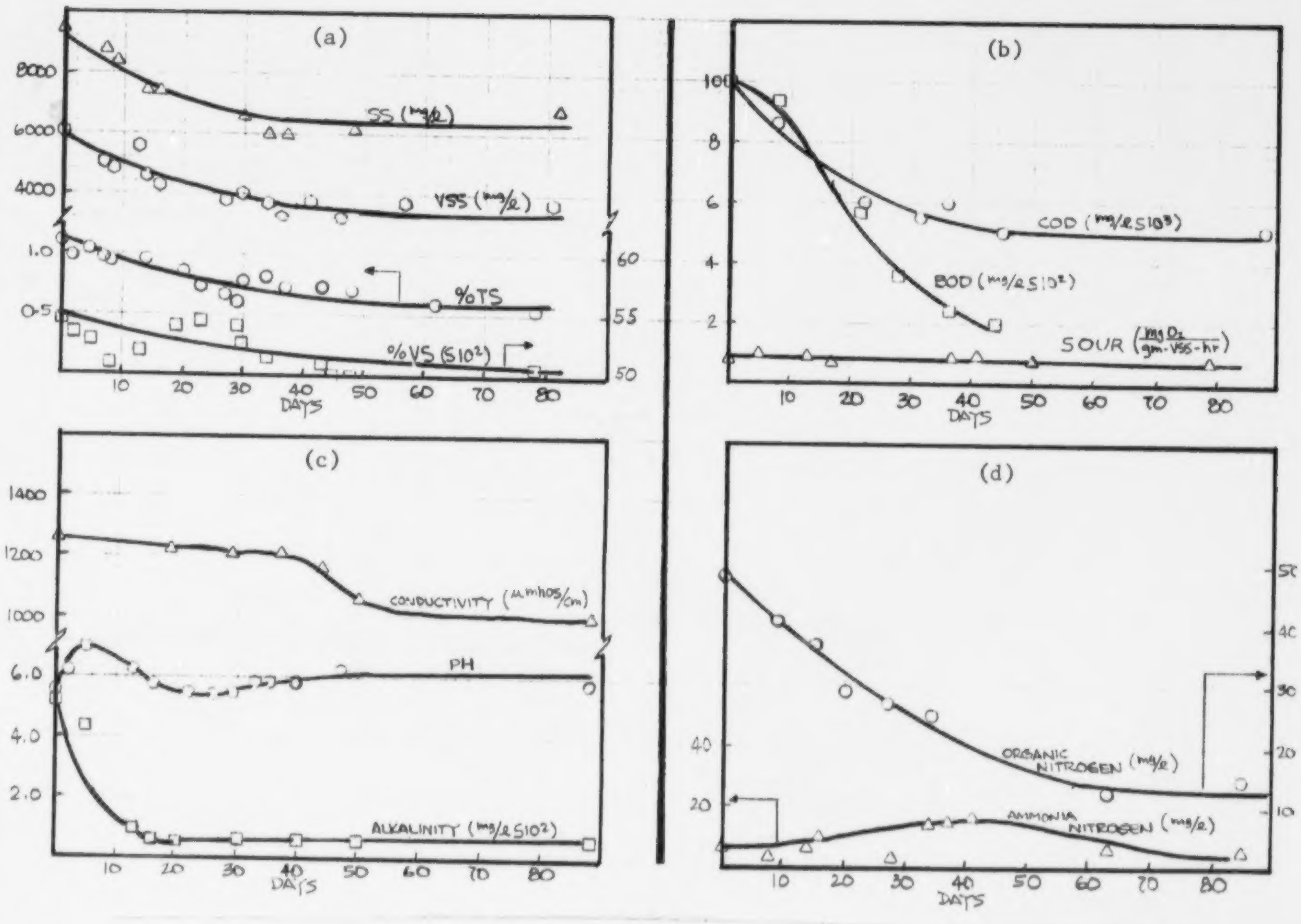


FIGURE 75. Poughkeepsie, N.Y. Thermal Sludge - Aerobic Stability Parameters

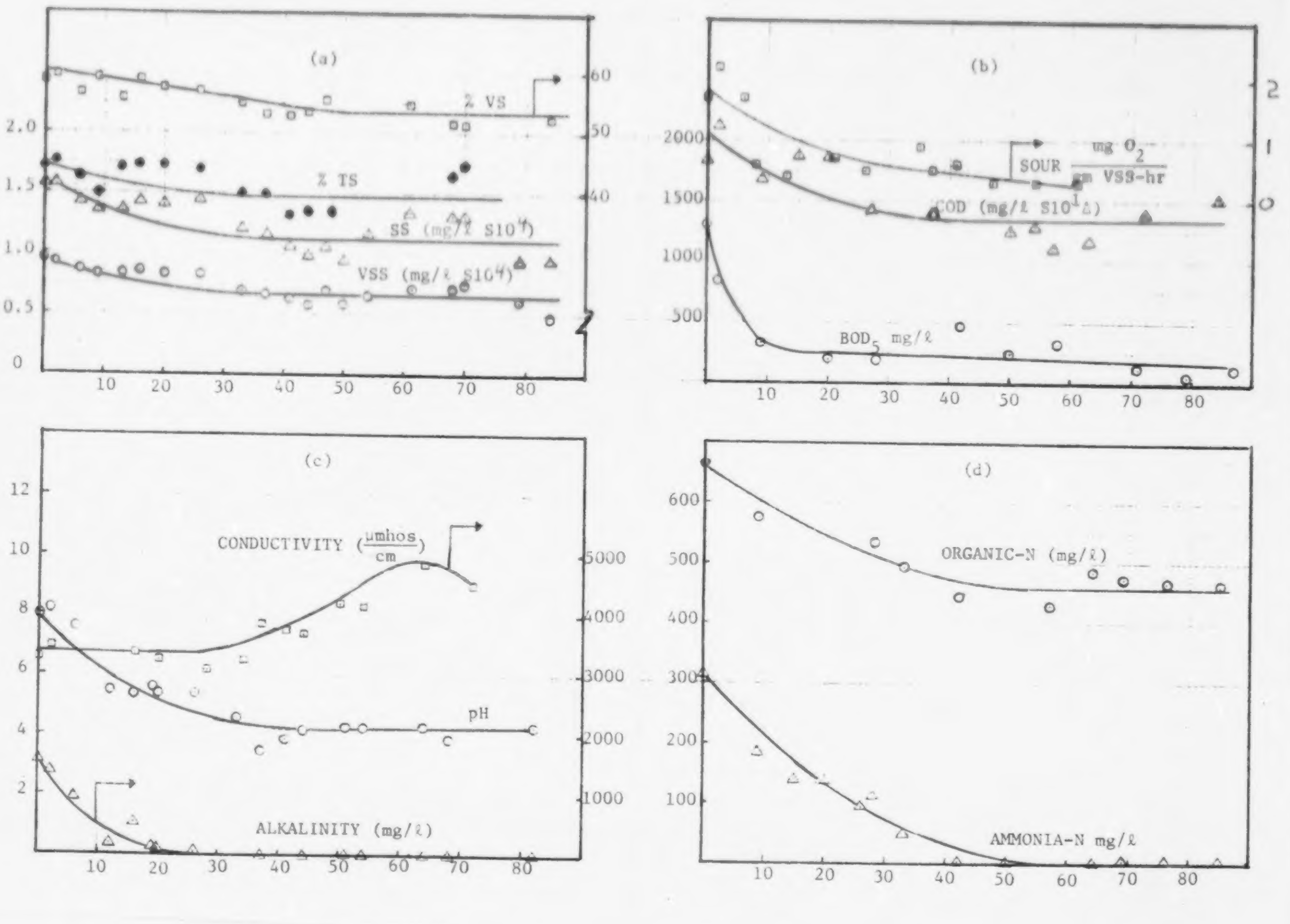


FIGURE 76. 26th Ward, N.Y.C. Anaerobic Sludge - Aerobic Stability Parameters

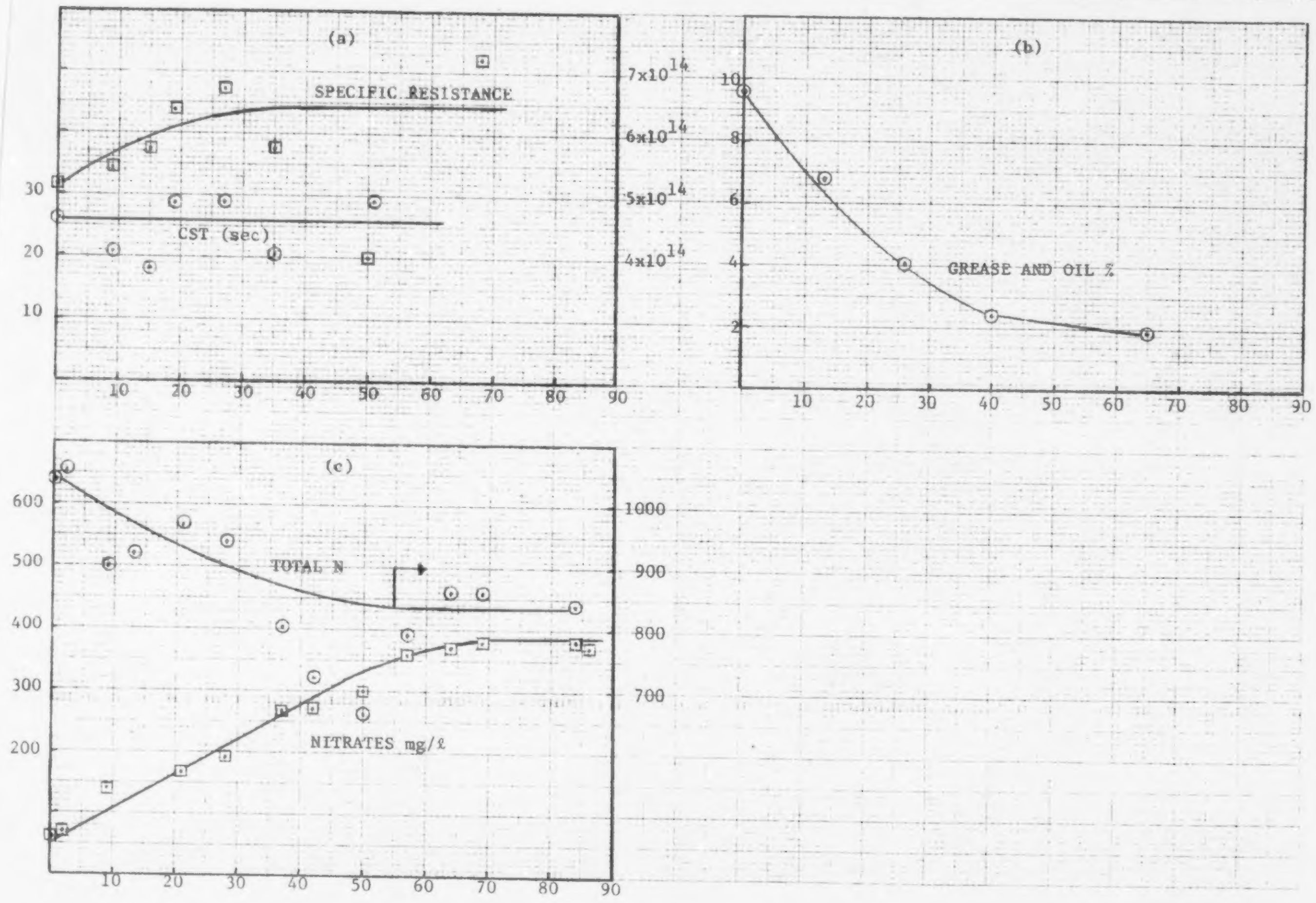


FIGURE 77. 26th Ward, N.Y.C. Anaerobic Sludge - Additional Aerobic Stability Parameters

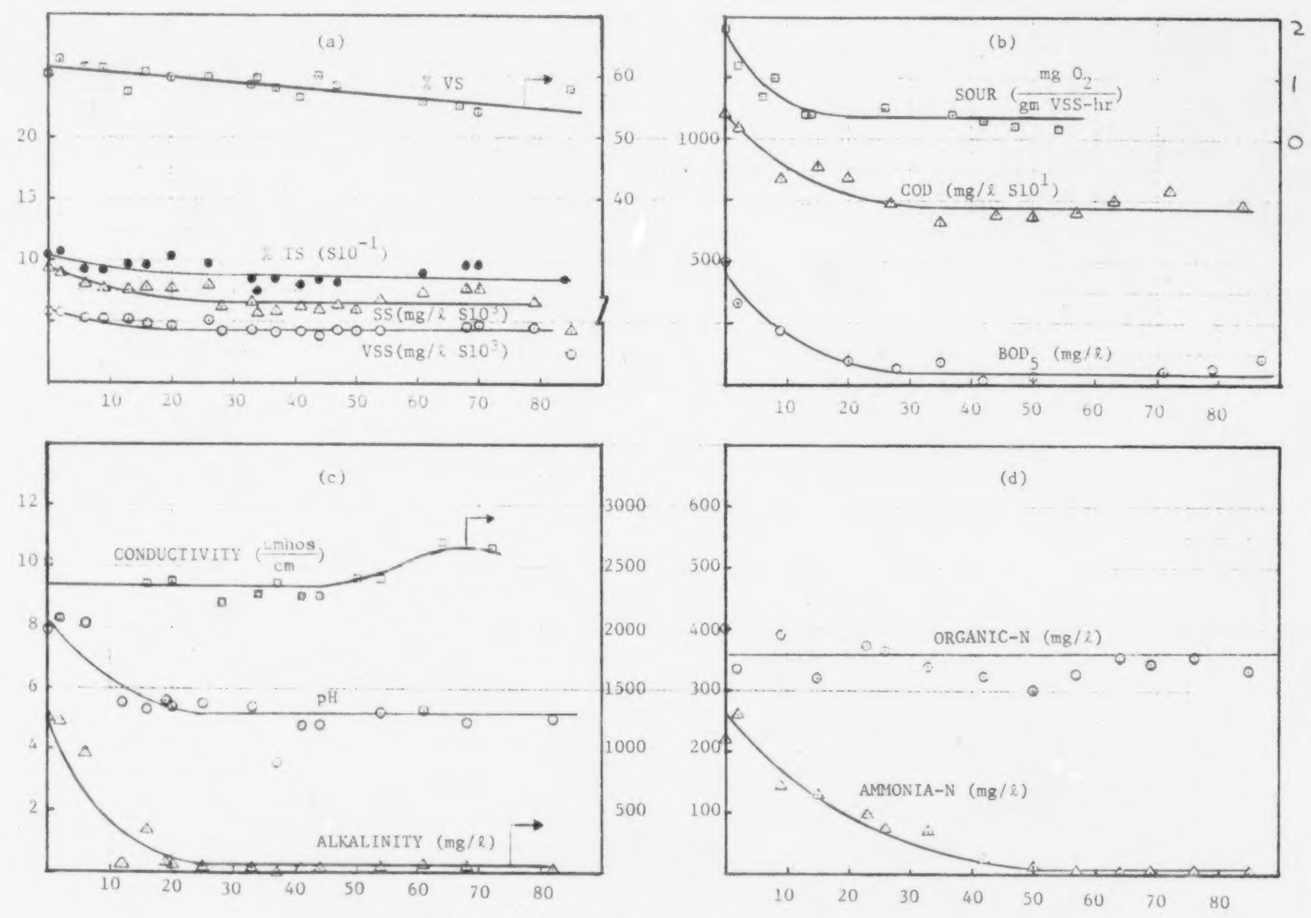


FIGURE 78. Jamaica, N.Y.C. Anaerobic Sludge - Aerobic Stability Parameters

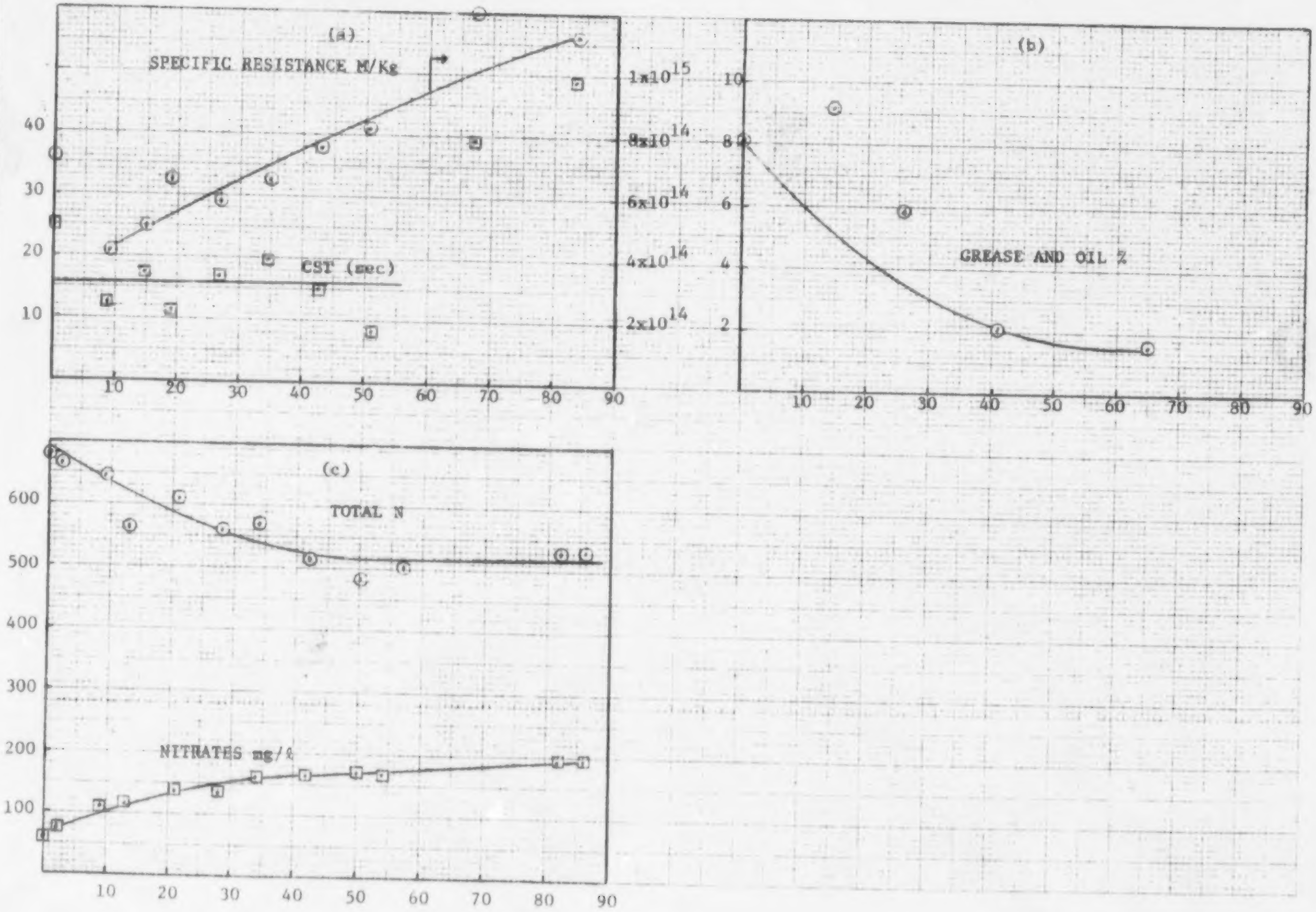


FIGURE 79. Jamaica, N.Y.C. Anaerobic Sludge - Additional Aerobic Stability Parameters

ANAEROBIC STABILIZATION

A total of 13 anaerobic digestion units were set up as illustrated in Figure 61 (Phase I) and Figure 63 (Phase II). In Phase I mixtures of digested sludge (primary and waste activated) from the Cedar Creek, New York Wastewater Treatment Plant was used as the seed (Unit 4 served as the seed control). Sludges fed to the individual units included: Cedar Creek, N.Y. primary sludge (Unit 1), Cedar Creek, N.Y. Waste Activated Sludge (Unit 2), (Summer Stony Point N. Y. aerobically digested sludge (Unit 3), Rockland County, N.Y. High Pressure Heat Treated Sludge (Unit 5), and Poughkeepsie, N.Y. Low Pressure Heat Treated Sludge (Unit 6). In presenting the data from these units in this section, a correction for the seed was not made. In the Phase II study no seed was used. Rather the sludges shown in Figure 63 (Units 7-13) were put directly into reactors and maintained from then on under anaerobic conditions. Actually only the sludge in Unit 7 had not been subject to anaerobic treatment prior to the additional anaerobic stabilization conducted. Units 8, 9 and 10 received anaerobically digested mixtures of primary and waste activated sludge from three different treatment plants in which the anaerobic digestion was being conducted at different loadings. Unit 11 received anaerobically digested primary and trickling filter sludges and unit 12 received primary sludge only. Unit 13 received anaerobically digested activated sludge. Table 41 gives the summary data of these anaerobic studies, giving the zero and 60 day results and the number of days required to reach steady state.

Phase I Seeded Sludges

Cedar Creek N. Y. - Primary Sludge (1)

Figure 80 illustrates the pattern of change for anaerobic stabilization of this sludge. Both total solids and volatile fraction exhibited significant reductions during the first 10 days and reached equilibrium values of 2.3 to 2.4% and 51 to 52% respectively after 20 days. BOD also declined rapidly during the same period and stabilized in the region of 2000 mg/l within 20 days. COD followed the same pattern but did not stabilize in value until 30 days of incubation. However, SOUR exhibited a different pattern, i.e., an increase over the first 20 days followed by a leveling off and a slight trend downward after 40 days. pH exhibited a similar pattern to SOUR except that the rise to a level value was reached in the first 5 days. Alkalinity should have slowly increased reflecting the increase in pH and ammonia. Although the alkalinity did increase during the run the data were erratic indicating analytical problems. Gas production (cumulative) and volatile acid concentration were mirror images of each other indicating stabilization during the first 10 days. Volatile acids and daily gas production were essentially negligible after 10 days. As indicated, a continual gradual increase in ammonia-N was observed as was a continuous decrease in organic-N. Consequently, total nitrogen was essentially constant.

Cedar Creek N.Y. Waste Activated Sludge (2)

As indicated in Figure 81 the pattern of change in parameters for this sludge was qualitatively similar to that for Cedar Creek Primary. Within a 10 to 20 day period, % total solids, % volatile solids, BOD, cumulative gas production, and volatile acids reached steady state values. Here again, pH remained virtually constant, ammonia-N slowly increased, organic-N slowly decreased, and COD reached a plateau in about 30 days. A different pattern was observed for SOUR which had an initial high rate and reached equilibrium after 6 days. Alkalinity exhibited a gradual increase over the first 30 days and then became constant.

Stony Point N.Y.-Aerobically Digested Sludge (3)

These data are presented in Figure 82. Solids destruction in this sludge was much less obvious than the previous sludges. Total solids decreased at a continuous low rate. Volatile solids data exhibited considerable fluctuation but also seemed to decrease at a very low rate. The pattern for the oxygen parameters was also quite different than previously. BOD drop-off was not as sharp and took almost fifty days to reach a steady value, while COD decreased relatively quickly reaching equilibrium within 25 days. Over the first 30 days alkalinity increased rapidly, slowly decreased over the next 20 days and then leveled off. SOUR exhibited a relatively rapid rise before leveling off at 25 days. The pattern for the other parameters was similar to that observed before except that it took somewhat longer for the gas production to reach steady state.

Cedar Creek Digested Sludge (Seed Material) (4)

This unit represents continued anaerobic digestion of sludge previously subjected to digestion. The results are given in Figure 83. Volatile solids and total solids exhibited virtually no change or a low linear rate of decrease. COD decrease was significant during the first 20 days but BOD removal was slight over the complete period of digestion. Gas production, volatile acids level, pH, ammonia-N, and organic-N exhibited similar patterns to that presented previously. The alkalinity pattern is again unexpected and probably due to analytical error because alkalinity values are much higher than justified by the ammonia-N level.

Rockland County Thermal Sludge (High Pressure) (5)

These results presented in Figure 84 are again similar to those from the units previously discussed. Solids changes were at a relatively low constant rate. Both BOD and COD dropped off relatively quickly and reached a steady state in 20 to 30 days. SOUR and pH remained relatively constant. Alkalinity and volatile acids increased, reaching a steady state value in about 20 to 30 days. No gas production was recorded. These latter data are not reasonable in light of the reported BOD and COD decreases unless volatile organics were formed in the thermal process and were released in the completely mixed digester. Again the general pattern of ammonia-N increase and organic-N decrease is noted.

Poughkeepsie Thermal Sludge (Low Pressure) (6)

The data for this unit is presented in Figure 85. Virtually no change in % volatile solids took place but a decrease in total solids from 3% to 2.4% after 30 days was observed. This result appears anomalous unless some of the fixed solids were destroyed. Actually a fall in % volatile solids occurred early in the run corresponding to the time period when % TS also decreased, but later in the run the % volatile solids rose again. Analytical errors are probably the cause of these data. Both the BOD and COD fell to steady state values. The BOD reaching steady state in 30 days, while the COD required almost 50 days. The SOUR exhibited a significant rise to a peak and then fell during the first 20 days. It remained at its original value for the remainder of the run. The alkalinity, pH, volatile acids, and gas production showed a pattern similar to that observed previously: alkalinity rose to steady state in 20 days, volatile acids fell to essentially zero in 20 days, pH remained essentially constant, and gas production was almost complete in 20 days. Total nitrogen, ammonia nitrogen, and organic nitrogen also exhibited their familiar pattern. Ammonia slowly increased, organic nitrogen decreased, and total nitrogen was constant.

Phase II Unseeded Sludges

Stony Point Aerobically Digested Activated Sludge (7)

The results of the anaerobic digestion of previously aerobically digested activated sludge are presented in Figure 86. Total solids showed a modest decrease from 0.88% to 0.75% in 30 days and then remained essentially constant; volatile solids also decreased similarly (60%-55%). Both COD and BOD declined in a similar fashion to that observed for the other anaerobic units in Phase I. BOD reached steady state in about 20 days at 80-85 mg/1. COD did not reach steady state for almost 40 days at about 6,500 mg/1. Volatile acids were very low (0-50 mg/1) during the run as was the gas production of only 3 liters.

The gas production has been plotted as flat but due to the large digester gas and liquid volume and small production, solubility effects make interpretation difficult. pH rose over the first 20 days of the run from 5.5 to 6.9 and remained steady. Alkalinity increased from 40 to over 1000 mg/1, reaching steady state in 50 days. Ammonia slowly increased from 0 to 60 mg/1 over the run and organic nitrogen decreased from 310 mg/1 to 260 mg/1. Thus total nitrogen remained unchanged. The major difference between the results here (Unit 7) and for unit 3 was the presence of the anaerobic seed in Unit 3. Some of the reactions were accelerated by the seed some were quantitatively due to the decomposition of the seed itself, rather than Stony Point Sludge.

26th Ward N.Y.C. Anaerobically Digested Primary & Waste Activated Sludge (8)

Figure 87 illustrates these results. Total solids fell from 3.4% to 2.9% at a rather uniform rate for most of the run. Volatile solids fell from 56.3% to 50% over the first 30 days and remained essentially constant. Both

COD and BOD reached steady state within 30 days at a COD of approximately 32,000 mg/l and BOD of about 1,100 mg/l. pH remained essentially constant at close to 7.2. Alkalinity rose from 4,600 to about 7,500 mg/l over the first 50 days. Gas production rose rapidly during the first 10 days and then very slowly increased. Volatile acids dropped sharply to zero in the first few days and remained at that level. The usual ammonia increase and organic nitrogen decrease took place. It is interesting to note the discrepancy between ammonia levels and alkalinity reported here. In an anaerobic digester the major buffer cation is ammonia. The bicarbonate alkalinity associated with ammonia is 3.57 mg/l alkalinity as $CaCO_3$ per mg/l of ammonia. In most of these runs the alkalinity was much higher than could be accounted for by the ammonia level. This may indicate analytical error or the presence of another buffer system.

Coney Island,N.Y. Anaerobically Digested Primary and Waste Activated Sludge(9)

The performance of this unit is given in Figure 88. The results are similar to those from the previous unit. Total solids decreased from 3.25% to 2.8% gradually over the 70 days of the run. Volatile solids decreased from 59.3% to close to 55% during the first 20 days and then remained constant. COD declined from 42,000 mg/l to approximately 34,000 mg/l in twenty days and then reached steady state. BOD fell from 4600 mg/l to 1,000 mg/l in 35 days. pH was constant at close to 7.4. Alkalinity gradually rose from 6,600 mg/l to 12,000 mg/l. Gas production rose rapidly for the first 10 days and slowly afterward to a value of about 50 liters total. Volatile acids were essentially zero throughout the run. The typical ammonia increase and organic nitrogen decrease took place.

Cedar Creek N.Y. Anaerobically Digested Primary and Waste Activated Sludge(10)

The results of this run are illustrated in Figure 89. This unit is essentially identical to unit 4 of phase I except that the sample being digested was taken at a different time. Both the % total solids and % volatile solids decreased slightly in the first 10-20 days and then remained constant at about 1.6% total solids and 59.5% volatile solids. Both BOD and COD declined to a steady state in 20-30 days; BOD reached 900 mg/l and COD 17,000 mg/l. pH increased slightly during the run. Alkalinity rose from 5150 mg/l to 6,500 mg/l gradually through the run. Gas production rose rapidly for 5 days and then quite slowly to a total accumulation of 20 l. Volatile acids were negligible throughout the run. Ammonia nitrogen again increased during the first 30-40 days and organic nitrogen fell during the same period. In general the results here were the same as those for unit 4.

Oyster Bay N.Y. Anaerobically Digested Primary & Trickling Filter Sludges(11)

This unit represents continued plug flow digestion of primary and trickling filter sludge previously digested in a complete mix digester. As shown in Figure 90, both solids parameters decreased to a steady state in less than 30 days. Total solids reached 6%, volatile solids approximately 53%. Both BOD and COD fell to steady state values in 30 to 40 days. BOD reached about 2700 mg/l and COD 62,500 mg/l. Again pH was fairly constant at close to 7;

alkalinity slowly increased from 4,800 mg/l to 6,800 mg/l in 40 days and volatile acids were essentially zero throughout the run. Gas production continued for a slightly longer period than previously and was complete after 20 days with the cumulative production of almost 50 liters. Again nitrogen forms exhibited the typical pattern. Organic-N decreased from 2,500 mg/l to 2,000 mg/l. Ammonia rose from 200 mg/l to 650 mg/l.

Yonkers N.Y. Digested Primary Sludge (12)

These data are given in Figure 91 and can be seen to be typical of the situation of continued anaerobic digestion of previously anaerobically digested sludge. Solids decreased at slightly higher rates initially and seemed to continuously decrease at a slow rate. Total solids reached 2.3% and volatile solids 44%. COD and BOD reached steady state in about 20 days at 25,000 mg/l for COD and 1,300 mg/l for BOD. pH was constant at 7.2, and volatile acids were negligible. Gas production was rapid during the first 10 days and was leveling off in 30 days at approximately 50 liters total production. Alkalinity rose from 4,900 mg/l to 6,300 mg/l in 10-20 days. Similarly, alkalinity, ammonia-N and organic-N reached steady state rather quickly in 10-15 days. Ammonia-N increased from 890 mg/l to 1,300 mg/l while organic-N fell from 1,100 mg/l to 700 mg/l.

Yonkers, N.Y. Anaerobically Digested Waste Activated Sludge (13)

Data for this unit are given in Figure 92. An air leak occurred after 40 days so the data are curtailed. However, these data again show similar patterns to that observed previously. Here total solids and volatile solids reached steady state in 20 to 30 days at levels of 1.65% and 62.5% respectively. COD reached steady state in about 30 days. The BOD data are suspect so are not discussed here. pH became steady at 7.4 after rising from 6.8 during the first 5 days. Alkalinity rose from 3,500 mg/l to 6,000 after 10 days. Volatile acids here were originally 140 mg/l but fell to zero in less than 10 days. Gas production was complete with 80 l in 15 days. The nitrogen changes observed were somewhat more erratic than previously but the same rapid rates occurred as in unit 12 and the decrease in organic-N quantitatively matched the increase in NH_3-N.

Additional Analyses

In addition to the results discussed, periodic measurements of grease and oil, and sludge filterability were made. Because of occasional errors in analyses not enough data on grease and oil was collected to yield definitive trends. In general, approximately 50% destruction of grease and oil was observed in most runs.

Table 41 and Figures 93-96 present the data on the capillary suction test and specific resistance. It can be seen that little change in these dewaterability parameters was observed during the 13 anaerobic runs. A few of the sludges exhibited a trend towards increasing resistance while a few showed the opposite effect or a decreasing resistance to dewatering as a result of extended anaerobic stabilization.

TABLE 41. ANAEROBIC UNITS

	1			2			3			4			5			6		
	Day 0	Day 60	Days to* Equ	Day 0	Day 60	Days to Equ.	Day 0	Day 60	Days to Equ.	Day 0	Day 60	Days to Equ.	Day 0	Day 60	Days to Equ.	Day 0	Day 60	Days to Equ.
BODmg/ℓ	5300	2000	15	5600	1300	20	1300	600	25	1400	1000	20	7100	5200	20	3500	1400	30
SOUR $(\frac{mg}{gmVS\text{-}hr})$	4.9	6.9	30	9.2	6.6	5	6.2	8.0	25	6.4	7.4	25	6.0	6.0	0	5.8	6.0	20
TS %	3.3	2.2	20	3.0	2.3	10	1.9	1.7	20	2.5	2.2	20	4.5	4.1	35	2.9	2.3	30
VS %	62	52	6	62	50	10	56	50	22	51	51	0	48	48	-	51	51	0
COD,mg/ℓ	33750	18000	30	28000	19000	40	20200	13000	30	31000	16000	25	50000	41000	20	30000	19000	50
Grease & Oil mg/ℓ	14.7	6	35	12.1	5.7	-	11	6	-	12.5	5	-	13	-	-	13.6	5.6	-
pH	6.8	7.5	15	7.3	7.4	0	7.4	7.4	0	7.4	7.4	-	6.9	6.9	0	7.0	7.2	20
Alk.mg/ℓ	6500	8000	30	6000	7900	35	4600	5600	60	6000	-	-	5600	8200	30	5000	7700	20
VA,mg/ℓ	1600	100	15	1500	20	20	220	80	10	1000	50	20	980	2200	30	760	30	20
gas,(ℓ)	0	95	10	0	97	10	0	30	15	0	37	15	0	0	-	0	85	10
NH_3-N	820	960	15	760	960	40	600	770	40	600	1000	40	760	1040	25	840	960	40
Org-N	1000	740	25	960	660	50	720	520	45	1000	720	30	1400	1190	25	960	680	50
CST,Sec	64	75	-	53	60	-	48	34	-	42	42	-	23	1.5	-	43	56	-
S.R.**	6.1	15	-	14	15	-	14	12	-	8	14	-	1.5	3	-	4.7	9.4	-

*Equilibrium

**Specific Resistance (m/kg x 10^{14})

TABLE 41. (cont'd)

	7			8			9			10		
	Day 0	Day 60	Days to* Equ	Day 0	Day 60	Days to Equ.	Day 0	Day 60	Days to Equ.	Day 0	Day 60	Days to Equ.
BOD mg/ℓ	130	-	20	3400	2000	20	4500	1800	-	1700	1400	20
TS %	0.88	0.74	30	3.4	2.9	-	3.2	2.9	20	1.8	1.6	0
VS %	60.5	55.5	25	56.4	50.4	30	59.4	54.7	20	63.5	59.1	10
COD,mg/ℓ	81000	64500	40	41500	31000	25	39500	31500	20	25000	17000	30
pH	6.2	6.9	20	7.2	7.4	0	7.2	7.8	0	7.0	7.3	0
Alk.mg/ℓ	40	1100	-	4600	7800	40	5300	6000	40	5200	6000	30
VA,mg/ℓ	30	-	0	48	-	0	0	-	0	0	0	0
Gas,(ℓ)	0	-	0	0	42	20	0	51^{+}	20	0	20^{*}	10
NH_3-N mg/ℓ	6.0	53	35	1100	1400	40	835	1350	20	800	950	35
Org-N mg/ℓ	360	275	35	1185	900	40	1200	810	25	980	610	35
CST,Sec	17	20	-	26	46	-	57	206	-	180	296	-
S.R.**	6.2	2.1	-	2.8	2.6	-	8.6	16	-	10.4	10.9	-

*Equilibrium **Specific Resistance (m/kg x 10^{14})

TABLE 41. (cont'd)

	11			12			13		
	Day 0	Day 60	Days to Equ.	Day 0	Day 60	Days to Equ.	Day 0	Day 60	Days to* Equ
BOD mg/ℓ	4200	2800	30	3100	1300	20	-	-	15
TS %	6.5	6.2	25	3.1	2.4	20	23	-	20
VS %	57	54	20	57.5	43.8	30	57	54	20
COD,mg/ℓ	72000	63000	30	41500	31000	25	39500	31500	30
pH	6.5	7.2	0	7.3	7.5	0	6.8	6.5	5
Alk.mg/ℓ	4800	7200	25	4900	6600	10	5100	6500	10
VA,mg/ℓ	0	-	0	25	-	0	1420	-	0
Gas,(ℓ)	0	58^+	15	0	50^+	30	0	82^+	10
NH_3-N mg/ℓ	200	600	25	870	1270	15	890	1450	15
Org-N mg/ℓ	2550	2000	10	920	700	10	1250	750	15
CST,Sec	40	200	-	100	279	-	285	350	-
S.R.**	3.1	14.8	-	10.2	98	-	5	26	-

*Equilibrium

**Specific Resistance (m/kg x 10^{14})

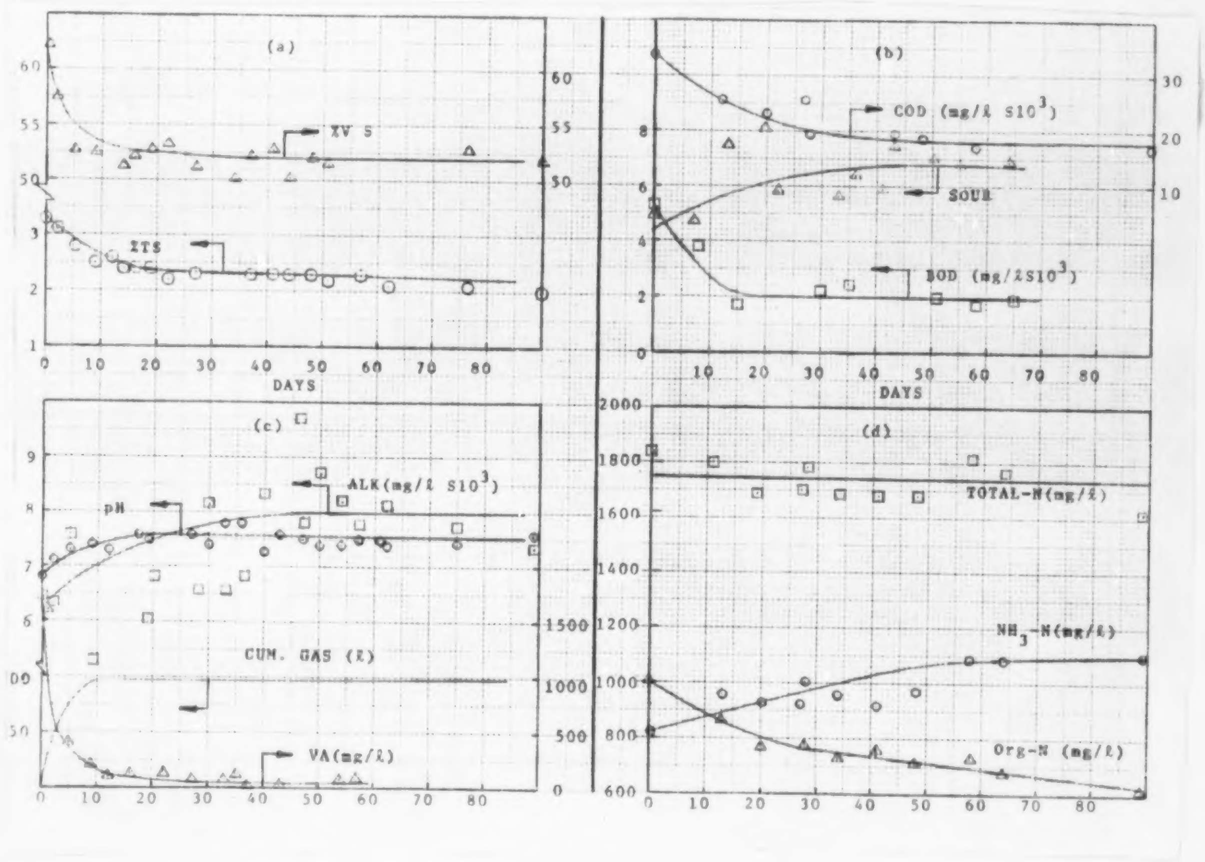


FIGURE 80. (Unit 1) Cedar Creek 25% Primary + 75% Seed - Anaerobic Stability Parameters

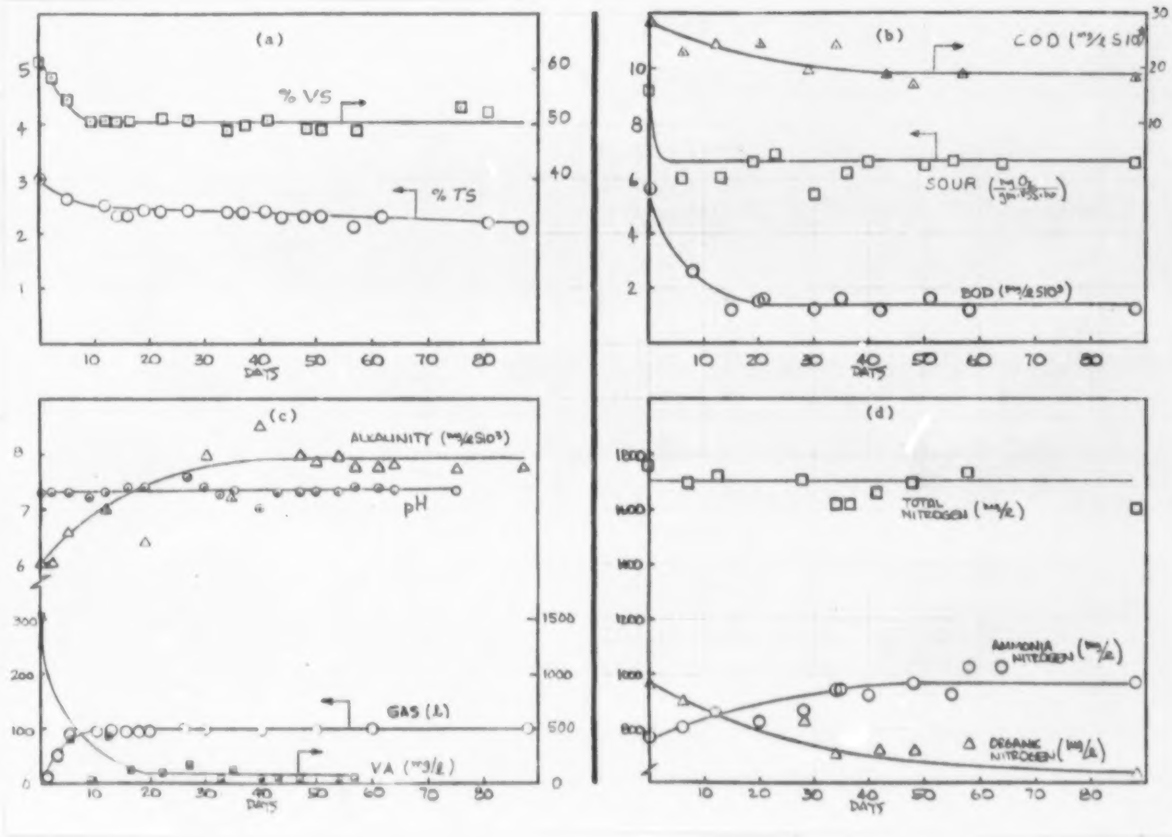


FIGURE 81. (Unit 2) 25% Cedar Creek Activated Sludge - 75% Seed - Anaerobic Stability Parameters

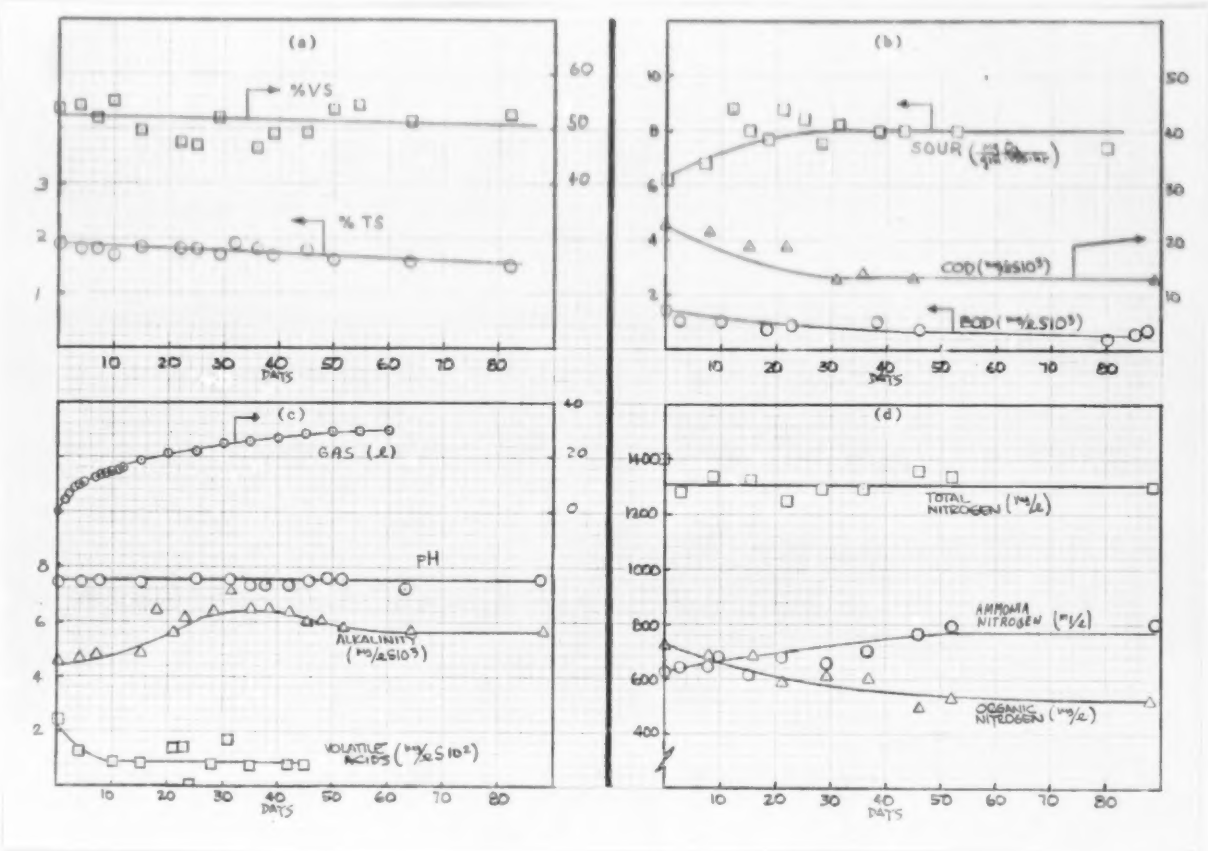


FIGURE 82. (Unit 3) 35% Stony Point + 65% Cedar Creek Seed - Anaerobic Stability Parameters

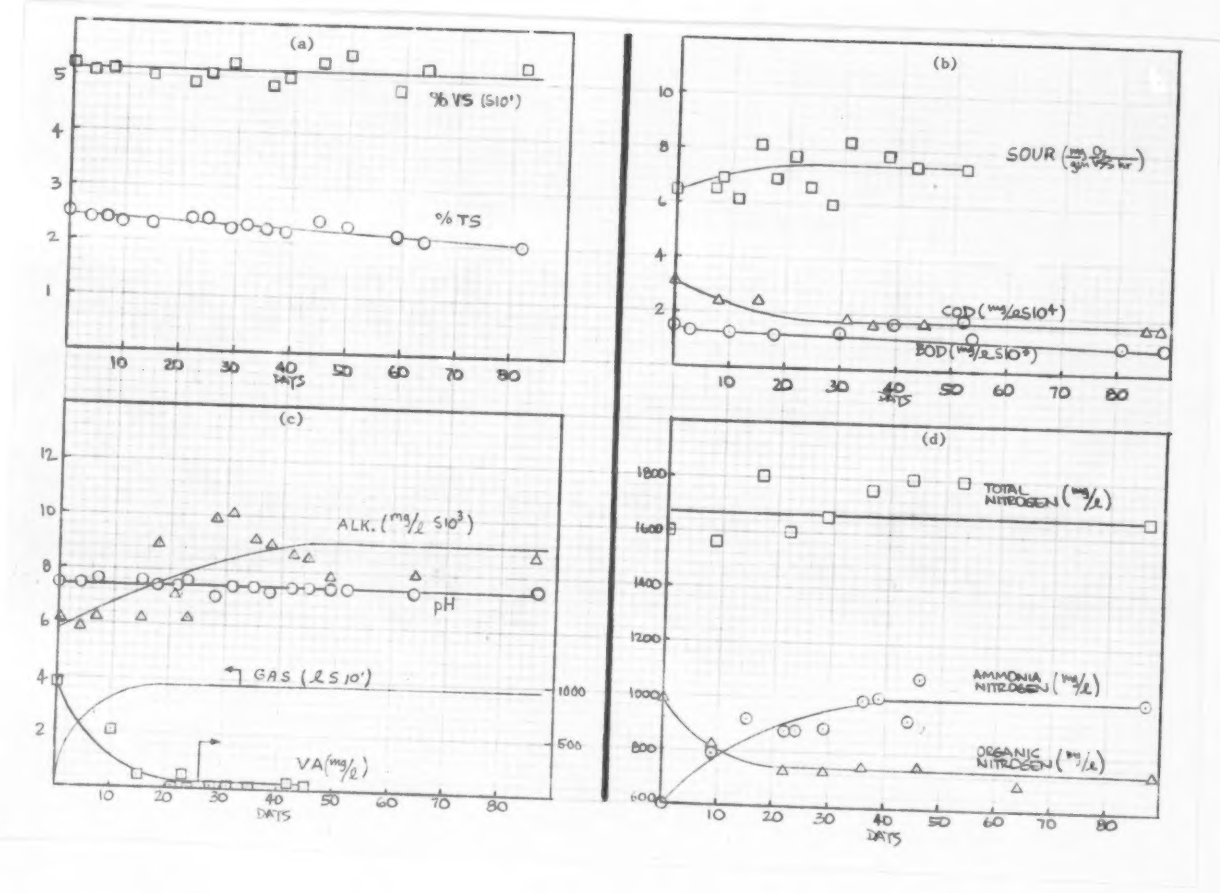


FIGURE 83. (Unit 4) Cedar Creek Seed - Anaerobic Stability Parameters

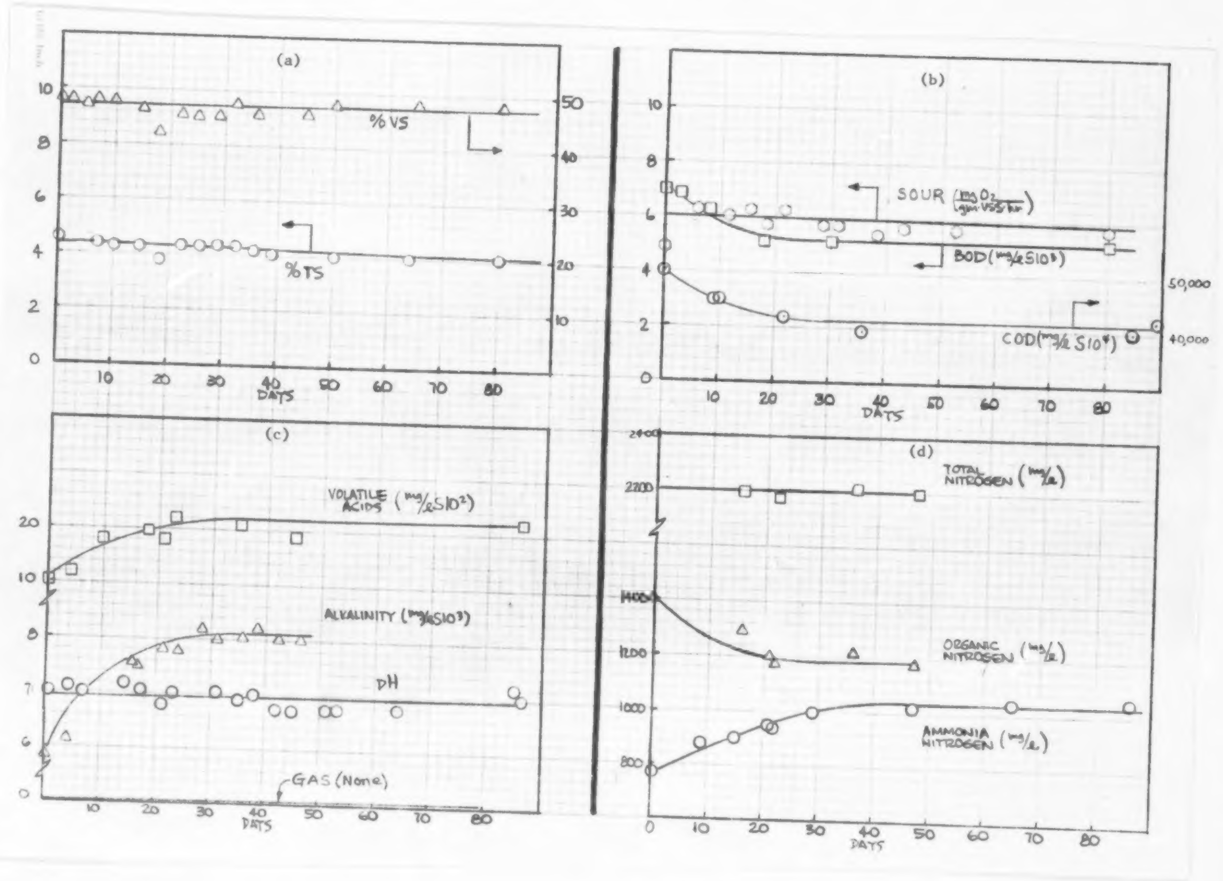


FIGURE 84. (Unit 5) Rockland County Thermal Sludge + 75% Seed - Anaerobic Stability Parameters

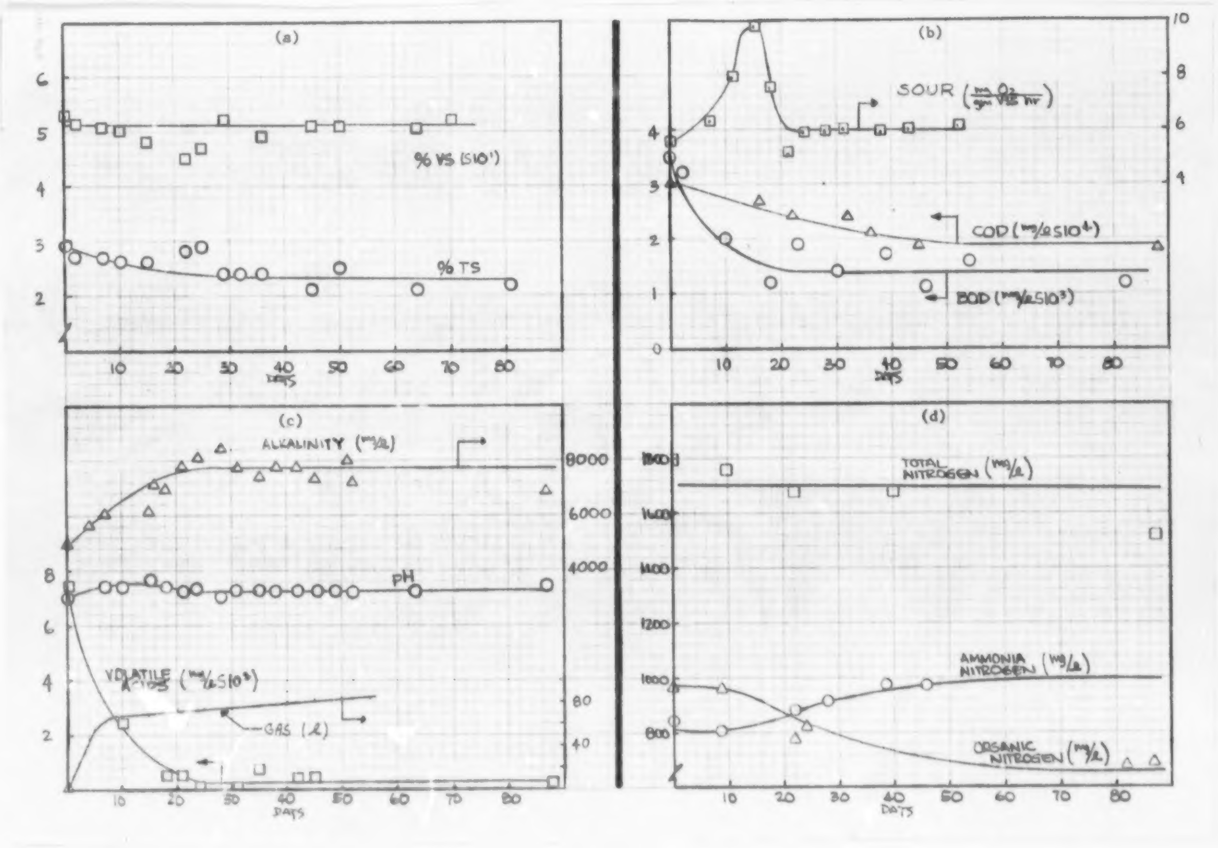


FIGURE 85. (Unit 6) 25% Poughkeepsie Thermal Treated Sludge + 75% Seed - Anaerobic Stability Parameters

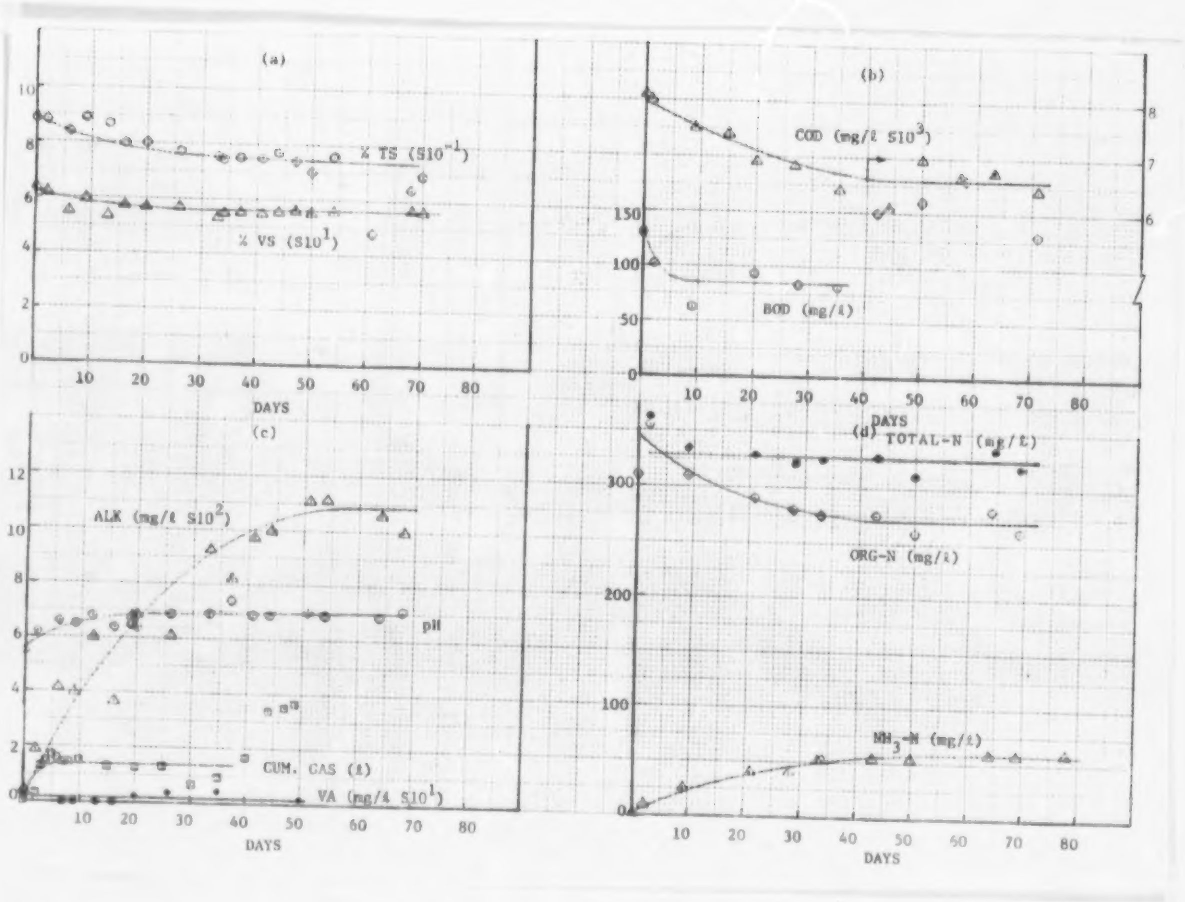


FIGURE 86. (Unit 7) Stony Point Aerobic Sludge - Anaerobic Stability Parameters

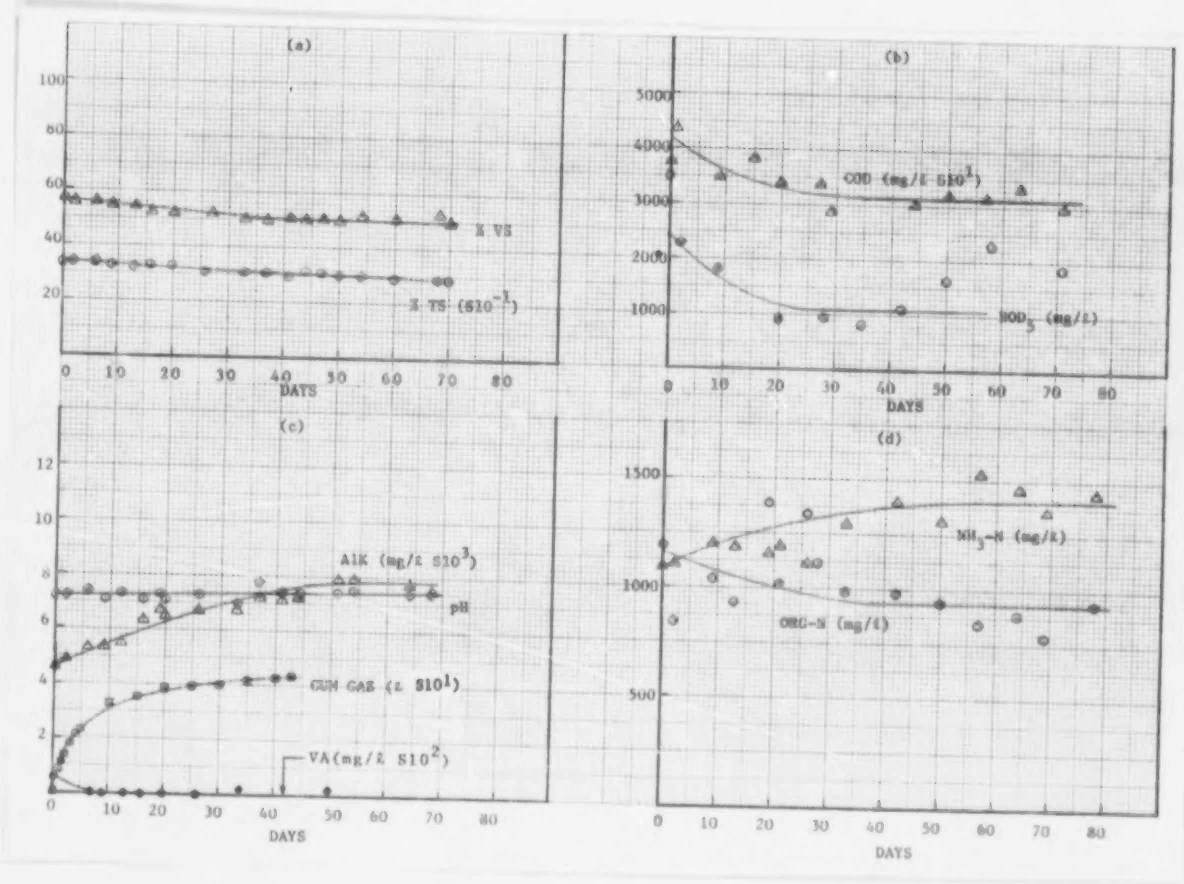


FIGURE 87. (Unit 8) 26th Ward Anaerobic Sludge - Anaerobic Stability Parameters

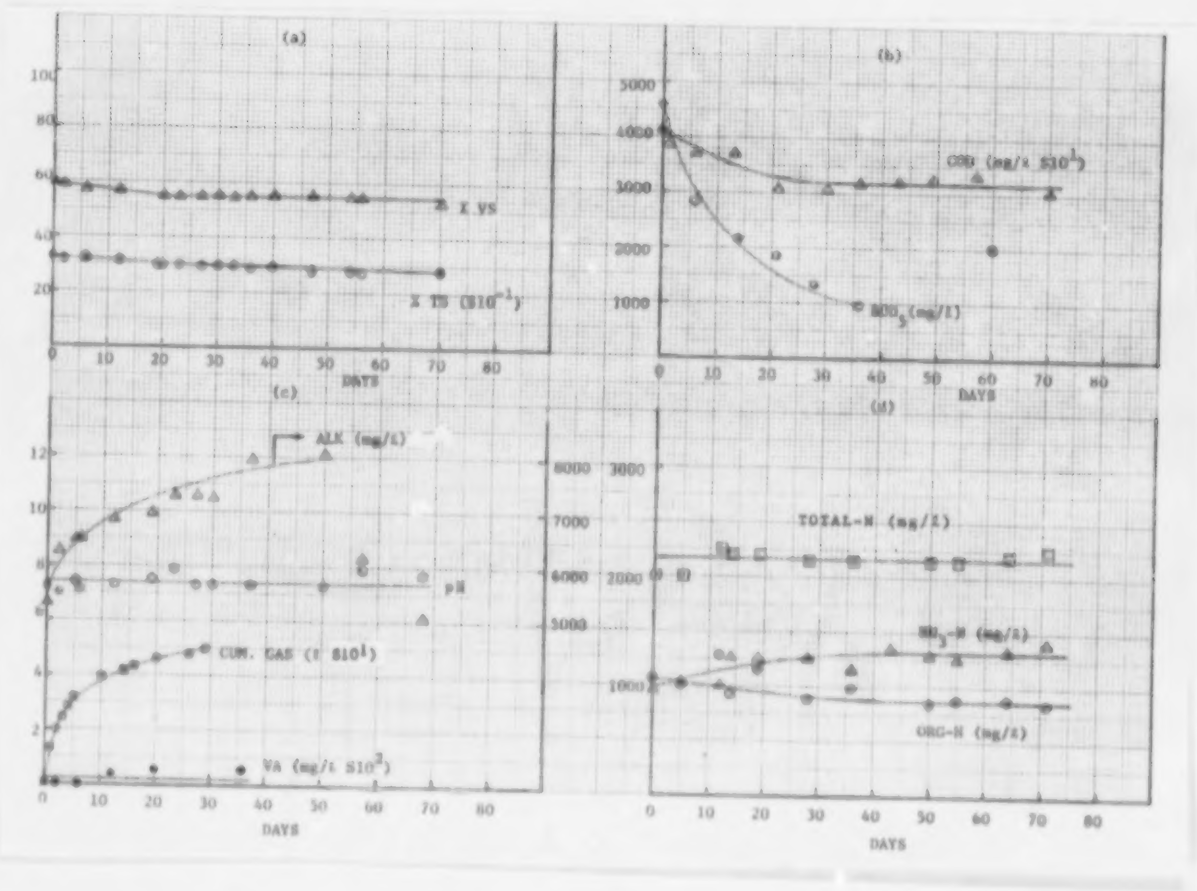


FIGURE 88. (Unit 9) Coney Island Anaerobic Sludge - Anaerobic Stability Parameters

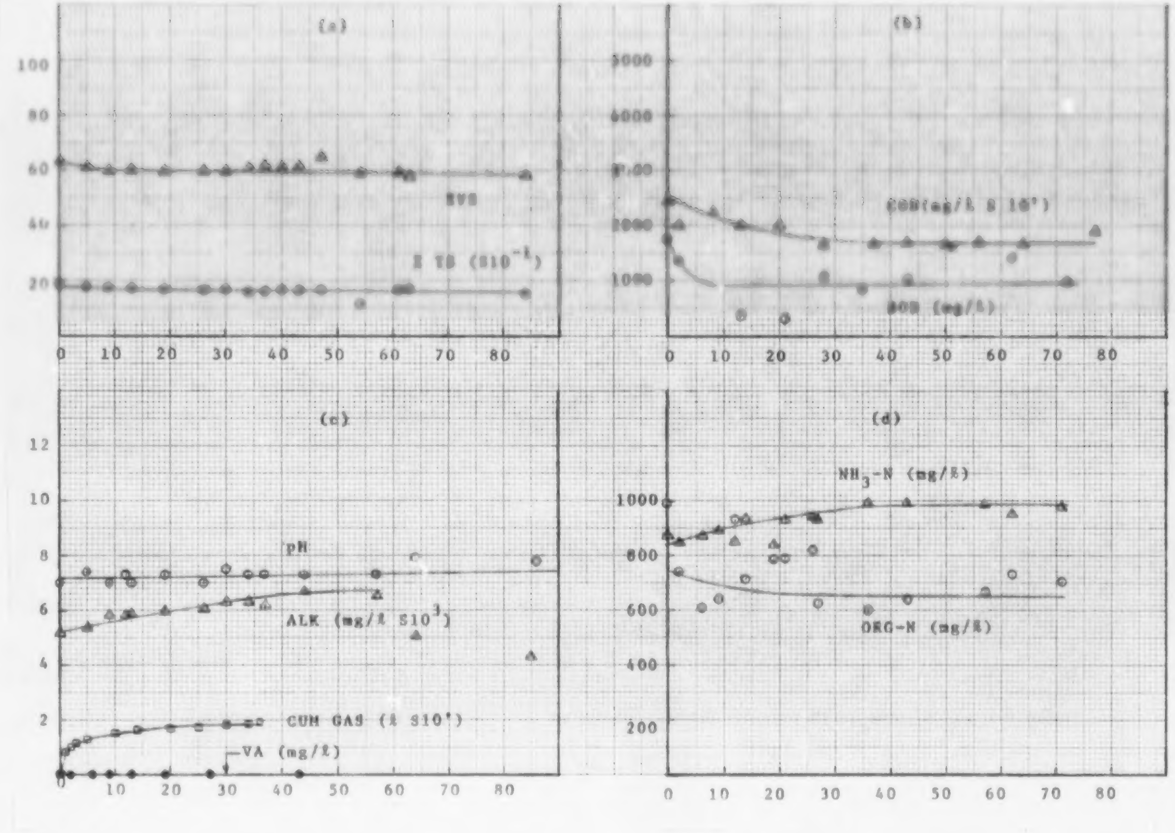


FIGURE 89. (Unit 10) Cedar Creek Anaerobic Sludge - Anaerobic Stability Parameters

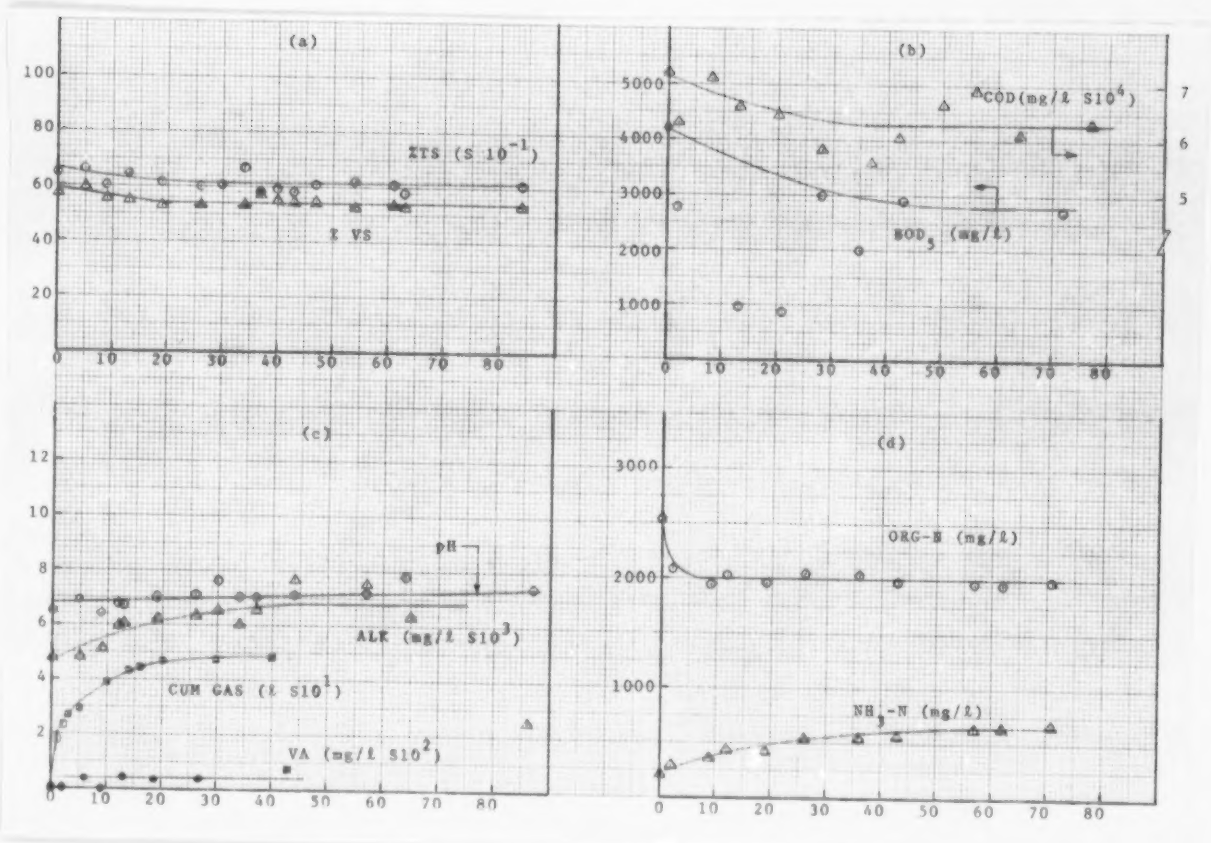


FIGURE 90. (Unit 11) Oyster Bay Anaerobic Sludge - Anaerobic Stability Parameters

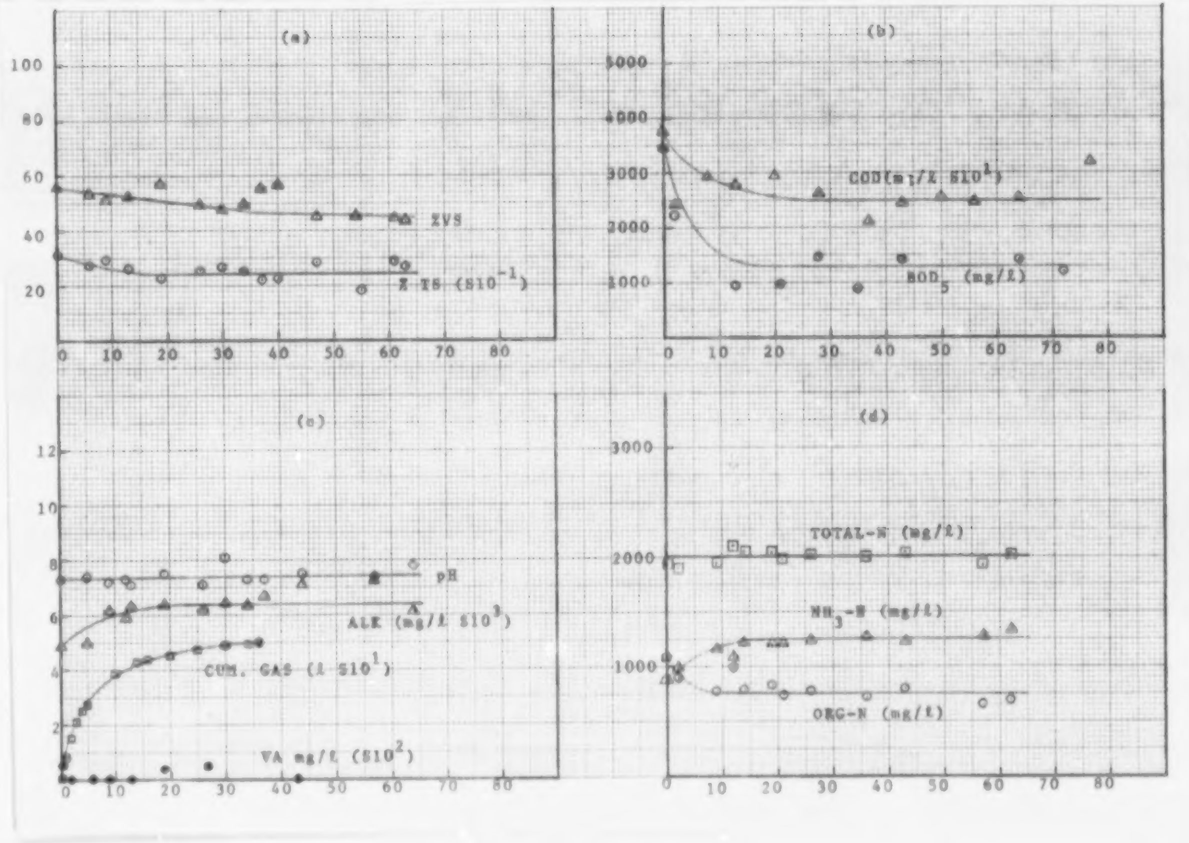


FIGURE 91. (Unit 12) Yonkers Anaerobic Sludge - Anaerobic Stability Parameters

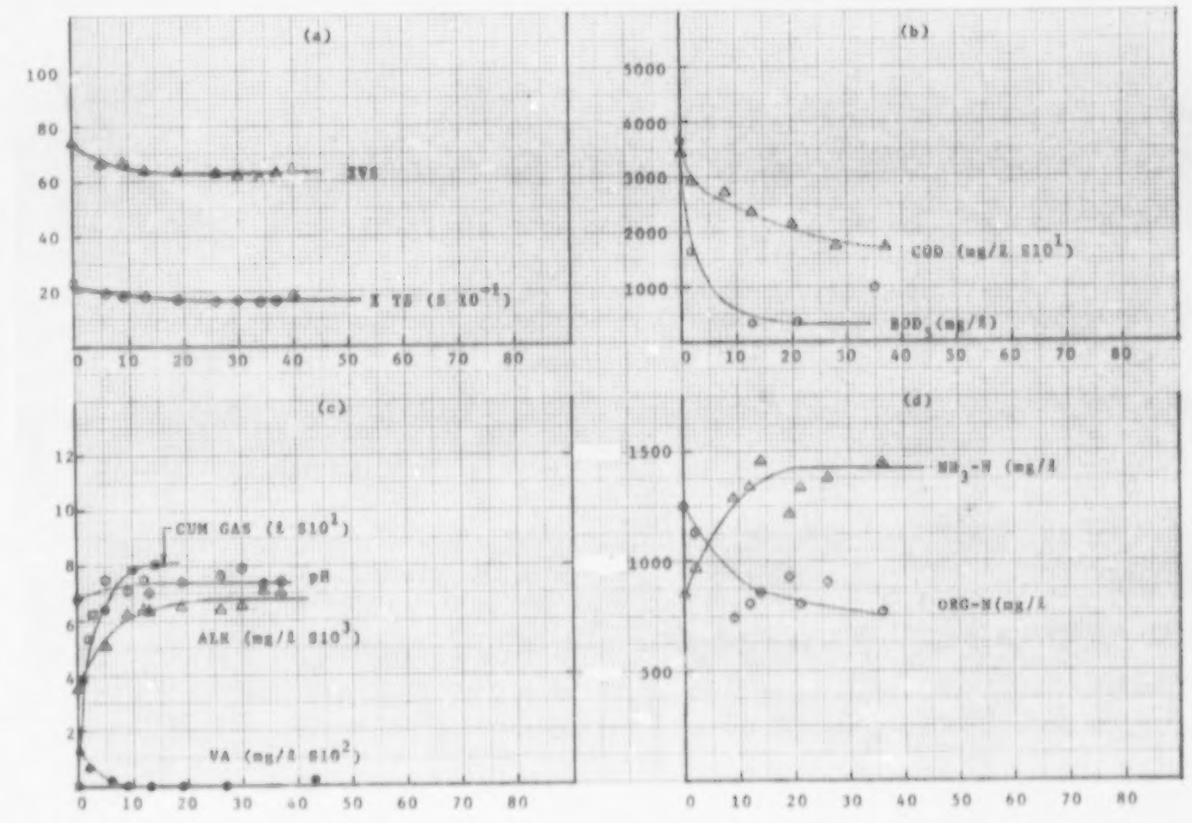
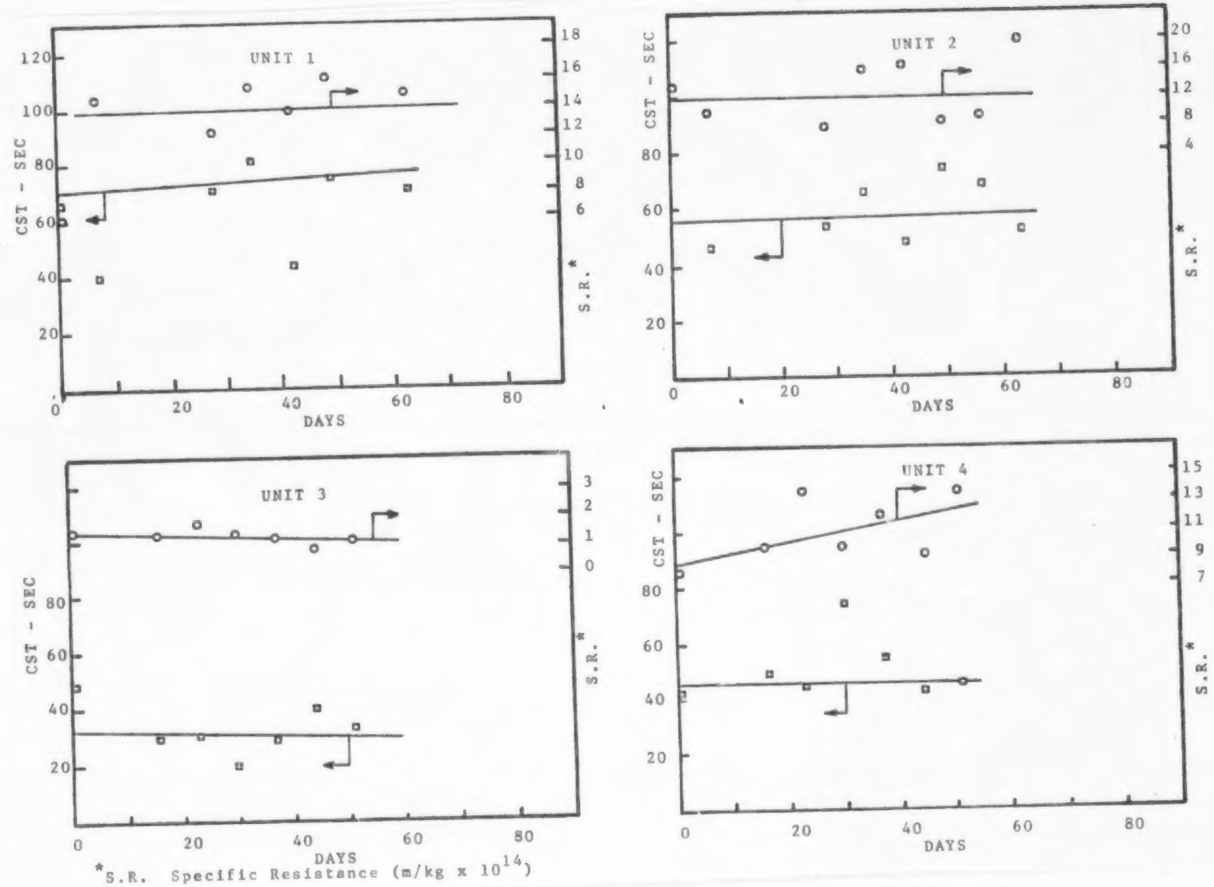
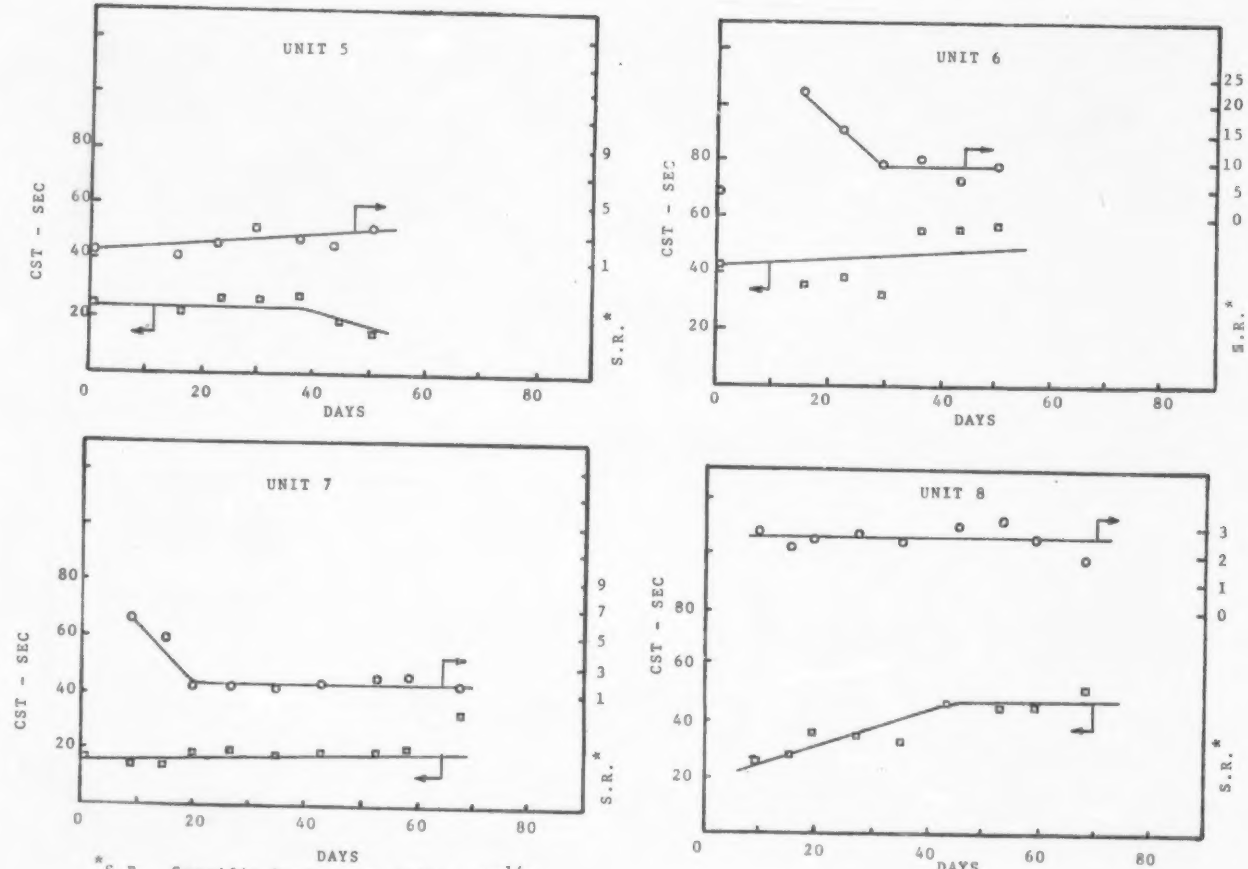


FIGURE 92. (Unit 13) Yonkers Anaerobic Sludge - Anaerobic Stability Parameters



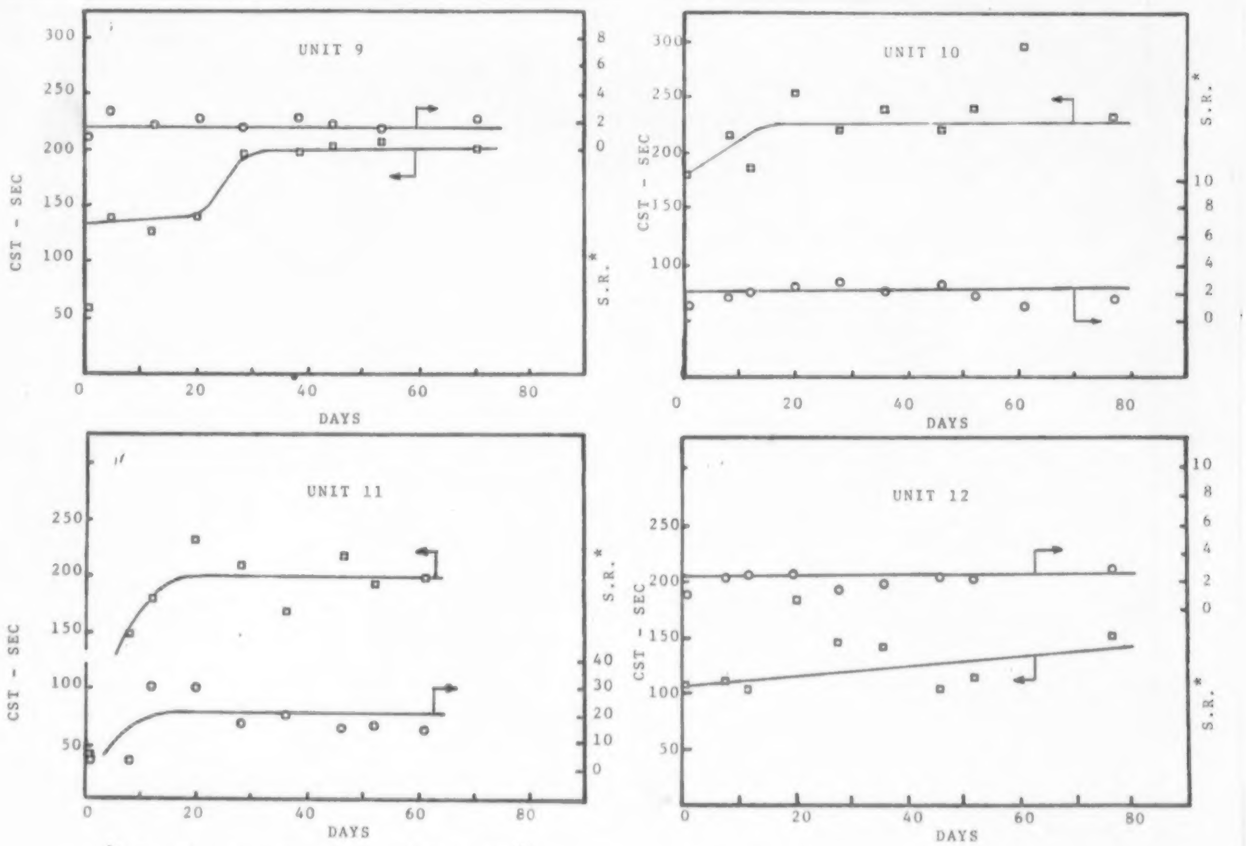
*S.R. Specific Resistance (m/kg x 10^{14})

FIGURE 93. Capillary Suction Test and Specific Resistance - Units 1-4



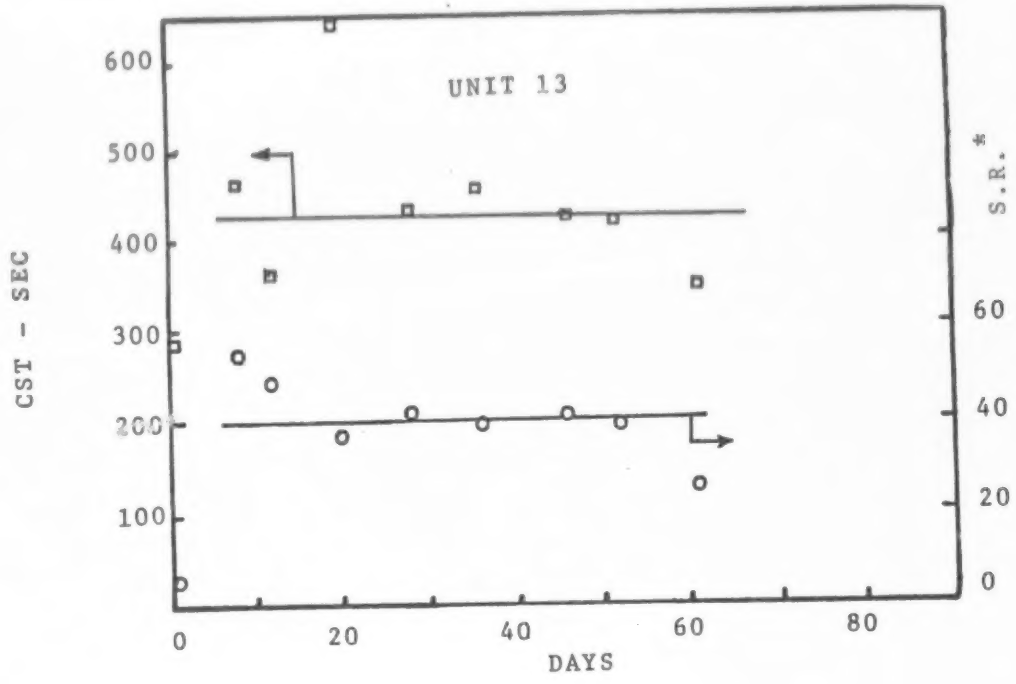
*S.R. Specific Resistance ($m/kg \times 10^{14}$)

FIGURE 94. Capillary Suction Test and Specific Resistance - Units 5-8



*S.R. Specific Resistance (m/kg x 10^{14})

FIGURE 95. Capillary Suction Test and Specific Resistance - Units 9-12



*S.R. Specific Resistance (m/kg x 10^{14})

FIGURE 96. Capillary Suction Test and Specific Resistance - Unit13

SECTION 8

DISCUSSION OF RESULTS

CHARACTERISTICS OF SLUDGES

Tables 34, 35, 36 and 37 present the characteristics of all of the sludges used in this study. It can be seen that both the aerobic and anaerobic sludges exhibited a wide range of processing characteristics. Sludges were taken from highly loaded activated aludge plants and those loaded at modest levels. The detention time in aerobic digestion that the sludges experienced prior to being collected for these experiments was in one case less than one day and in another case as long as 21 days. The HRT of the anaerobic sludges ranged from 13 days to 35 days. The feed to the anaerobic digester included raw primary sludge, waste activated sludge alone and mixtures of raw primary and waste activated or trickling filter sludges. In general all of the sludges used were within the range of processing parameters normally used in practice.

AEROBIC DIGESTION OF SLUDGES

Nine sludges, five which had been subjected to aerobic treatment, two which had been subjected to heat treatment, and two which had been subjected to anaerobic digestion, were aerobically digested in the studies conducted under this project. A summary of the pertinent data is presented in Tables 39 and 40. These data were selected from the plots of Figures 65 through 79. The selected data in Tables 39 and 40 include the sludge parameter at time 0, after 60 days of digestion and the time required to reach a steady state value of the parameter. A total of 15 sludge parameters are recorded in these tables. Rather than discuss these individually they will, in the discussion which follows, be grouped as follows: solids parameters, oxygen demand parameters, pH-alkalinity-conductivity, nitrogen forms, dewatering characteristics-grease.

Aerobic Digestion of Aerobic Sludges

Similar patterns of change in parameter magnitudes were observed for all of the aerobic sludges (Beacon, Cold Springs, Musconetcong, Stony Point summer and Stony Point winter). In most cases, all forms of solids decreased relatively quickly over the first 20-30 days and then rather slowly. Oxygen demand exhibited a similar pattern with higher fractional decreases in BOD and SOUR than COD. Only the Stony Point winter sludge was different, exhibiting virtually no change in SOUR. However, the final SOUR of this sludge was the same 0.4 mg O_2/g VSS-hr as for all the other aerobic sludges. Perhaps the low initial BOD of the Stony Point winter sludge (130 mg/l) accounts for the constant SOUR.

All changes in pH-alkalinity and conductivity were similar, again with the minor exception of the Stony Point winter sludge. Alkalinity rapidly decreased to quite low levels in about 20 days; less than 10 for Stony Point winter. The pH first decreased to a minimum over the first 20 days (usually into the pH range 4-5) and typically returned to the original pH value. The conductivity exhibited the reverse pattern, first rising and then falling. The conductivity peak occurred a few days after the pH minimum. The Stony Point winter sludge exhibited essentially no change in conductivity or pH. The shift in conductivity is a response to the increase in hydrogen ion concentration (low pH) because of the high specific conductance of this ion.

The nitrogen forms pattern was again similar for all units except the Stony Point winter sludge. Organic nitrogen decreased rapidly as a result of the endogenous metabolism of the cellular material. The nitrogen is released into the liquor in the form of ammonia resulting in the initial increase of this nitrogen form. Ammonia removal primarily by nitrification and to a minor extent by stripping takes place concurrently. Once the organic nitrogen breakdown is complete there is no feed of ammonia to the system so the ammonia level peaks and starts to decrease. It is important to note that this ammonia peak correlates well with the stabilization of SOUR, BOD, organic nitrogen and to a lesser extent, with alkalinity. Undoubtedly the pH changes observed are due to the changes in nitrogen forms and stripping of ammonia and carbon dioxide. Unfortunately, measurement of nitrate in solution and ammonia and carbon dioxide in the off gas of aerobic digesters was not conducted. It appears that the Stony Point winter sludge was well digested prior to the start of the run. The specific resistance and CST measurements indicated in general no significant change as digestion proceeded, although there was a tendency for a rise and fall pattern as shown on several of the curves.

In all cases, significant grease removal took place (greater than 50%) over the first 20 to 30 days for all sludges. This along with nitrate formation may account for the drop in pH observed during the initial period of stabilization.

Aerobic Decomposition of Heat Treated Sludges

The heat treated sludges (Rockland and Poughkeepsie) exhibited similar patterns of change in solids, oxygen demand, nitrogen forms and grease as for the aerobic sludges discussed above. However, the pH pattern was different. For both of these sludges the pH first rose and then returned to near the original level. This rise then fall is what would normally be expected in batch aeration of sludge rather than the pattern observed previously because as ammonia is released during protein breakdown, ammonium bicarbonate would tend to be formed first followed by nitric acid as nitrification of the ammonia occurs. It may be that in the five aerobic sludges discussed above, a large population of nitrifiers was present at time "0" which would foster rapid initial nitrification; while heat treatment would retard nitrifiers, thus delaying the onset of nitrification. Figure 74 indicates that specific resistance decreases and CST remained constant for one of these sludges while there was an increasing trend for both parameters with the other sludge. No reason can be given for this pattern.

Aerobic Digestion of Anaerobically Digested Sludges

The pattern of parameter change with time of aeration was again similar to that observed previously in aerobic stabilization. The main area of difference was in the pH-conductivity pattern and in the ammonia nitrogen pattern. For aerobic digestion of anaerobic sludge it was found that pH rapidly decreased and then remained constant while conductivity rose as pH fell. The ammonia nitrogen at time zero was at a high level (due to protein breakdown under anaerobic conditions with no possibility of nitrate formation). Both the organic and ammonia nitrogen decreased with time as aerobic stabilization converted ammonia to nitrate. Thus no ammonia peak was observed. The specific resistance rose while the CST remained constant.

SUMMARY OF AEROBIC STABILIZATION

The results obtained for aerobic decomposition indicate a consistent pattern set for a group of parameters. All forms of solids, all forms of oxygen demand, grease, alkalinity and organic nitrogen typically exhibited a relatively rapid decrease to a steady state value. The decreasing pattern could probably be fit by a first order or retardent type of curve. Changes in pH, conductivity, ammonia nitrogen, specific resistance and CST depended on the source of the unstabilized sludge. The changes in these latter parameters were consistent within each sludge source and depended on the initial population of nitrifiers present and the initial level of ammonia nitrogen.

Although a reproducible pattern of change in a number of common parameters was observed, no quick test emerged to indicate when sludge could be considered stabilized. Perhaps the specific O_2 uptake rate (SOUR) parameter could prove to be valuable as an indicator of stabilization as most sludges seemed to stabilize in the 0.4-1.0 mg O_2/gm VSS·hr. Being a specific parameter, it has the advantage of giving the same answer for most aerobic sludges. Other parameters such as solids, COD, etc. will have variable concentrations when stability is reached, depending on the concentration of the original sludge. Therefore for the individual treatment plant, which would typically operate at uniform concentrations, a sludge could be considered stable in respect to any of the parameters tested, when given aerobic treatment as provided in these experiments. For example, when given 30 to 40 days of aerobic digestion treatment, a sludge would be stable in respect to COD. In general, stabilization occurred in the detention period of 20 to 40 days as evidenced by steady state values for a number of parameters but continuous testing with time is required to identify the stabilization pattern.

ANAEROBIC DIGESTION OF SLUDGES

Thirteen sludges were subjected to prolonged anaerobic stabilization. These included raw sludges, mixtures of raw sludge and waste activated or trickling filter sludge, waste activated sludge alone, heat treatment sludge, sludge which had been previously anaerobically digested and sludge which had been previously aerobically digested. A summary of the parameter changes cbserved is given in Table 41. These values were selected from Figures 80 through 92.

A similar pattern of changes in measured parameters was observed for all of these units regardless of the source of the sludge. There are several discontinuities in the general patterns observed but these are felt to be due to experimental difficulties which were discussed previously rather than basic differences in the pattern of stabilization. Quantitative differences between units can be traced to the degree of stabilization which had taken place in these sludges prior to the start of the stabilization in this study.

The basic pattern observed includes:

1) Modest continuous decreases in both total and volatile solids. In some cases a rapid initial decrease took place followed by a slow gradual decrease.
2) Relatively significant reductions in BOD and COD in a 20 to 30 day period, with the BOD generally decreasing more rapidly than the COD.
3) A rapid decrease in volatile acids occurred concurrent with gas production except for unit 6 Rockland County thermal sludge which probably was inhibitory and volatile acids increased to 2200 mg/ℓ. Except for unit 6, gas production ended when the volatile acids were consumed. As would be expected, alkalinity rose as the volatile acids fell. pH exhibited little change except for an occasional slight rise during the gasification period in some units.
4) Organic nitrogen decreased and was almost exactly balanced by an ammonia nitrogen increase. This is anticipated as under anaerobic conditions all nitrogen released from organic breakdown must be in the ammonium ion form. The rate of change in these parameters decreased as the run progressed until steady state was achieved.
5) As indicated previously, essentially no change in sludge filterability took place and grease was reduced typically by more than 50%.

LEAD ACETATE-HYDROGEN SULFIDE ODOR TEST

One of the tests described in the experimental procedures section was the centrifuge button test. In this procedure the stability of a centrifuged button of sludge is determined by the length of anaerobic incubation required to blacken a lead acetate paper. The release of H_2S is the agent for blackening the paper. The more stable the sludge, the longer it should take to blacken the paper. Test results obtained during the Phase I portion of the study are given in Figures 97 and 98. In Figure 97 are plotted the results of the anaerobic stabilization of the sludges in units 1 through 6. It can be seen that all sludges were relatively unstable at time zero except unit 3 which contained seed plus aerobically digested sludge. The most unstable sludge initially was unit 1 which contained primary sludge and turned the lead acetate paper black in one day. After 10 to 15 days stabilization, a sudden change took place in that unit 1 became the most stable sludge followed by unit 4, the seed control. Unit 2 containing activated sludge became more stable than unit 3 which contained aerobically digested sludge. Units 5 and 6 were equally unstable at time zero according to this test but as the run pro-

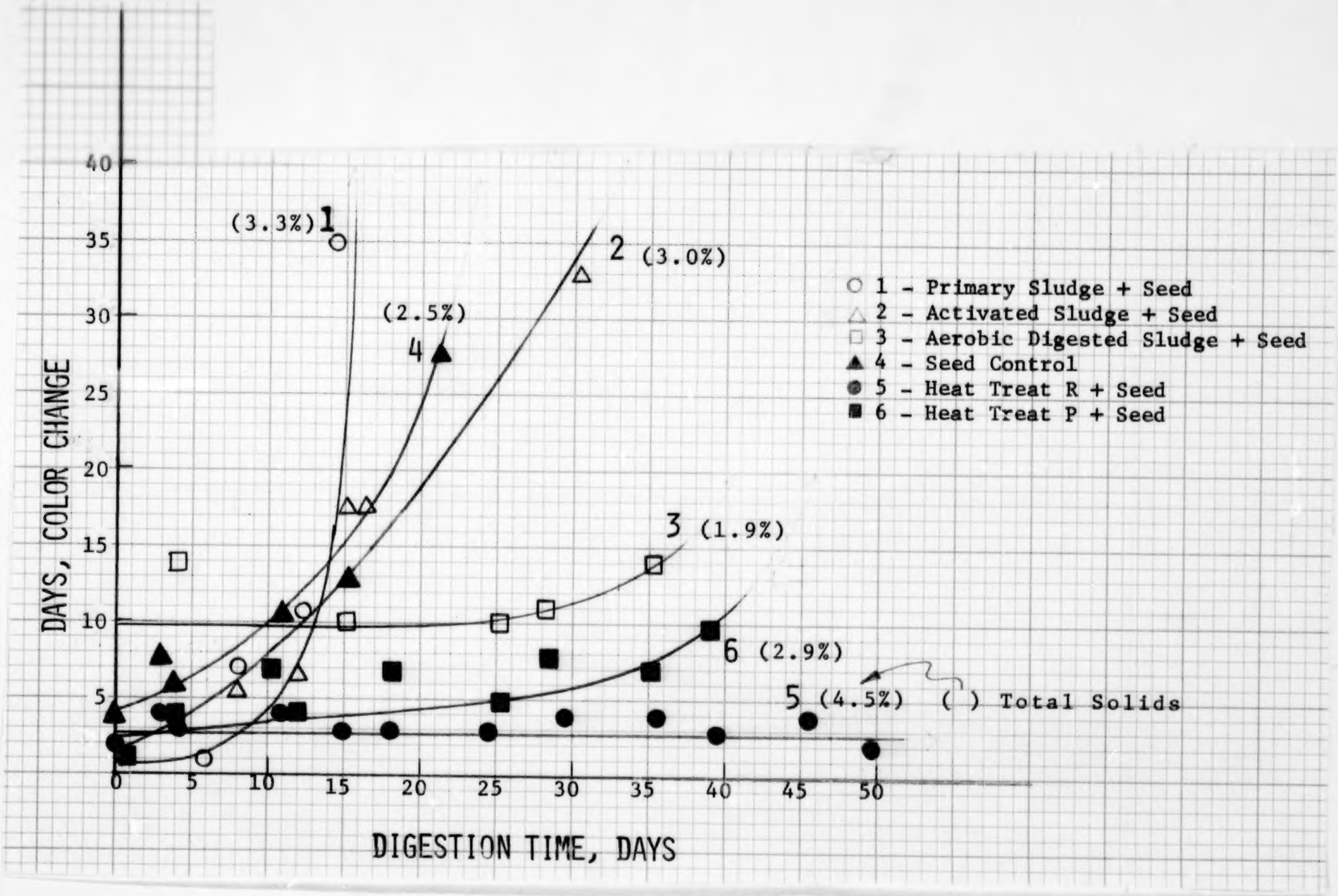


FIGURE 97. Lead Acetate - Hydrogen Sulfide Odor Test - Anaerobic Sludges

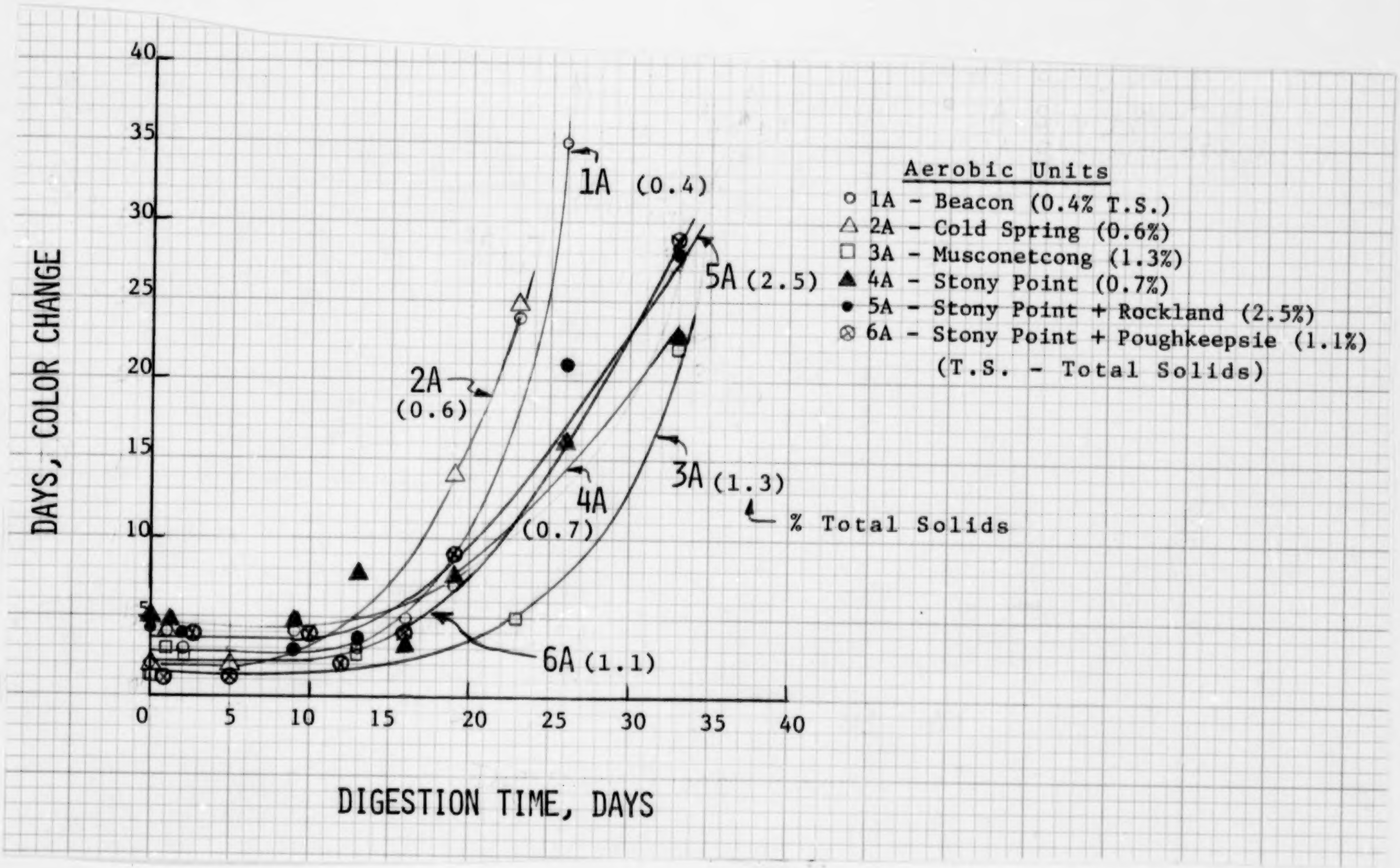


FIGURE 98. Lead Acetate - Hydrogen Sulfide Odor Test - Aerobic Sludges

gressed, unit 6 became more stable than unit 5 but both were unstable with respect to odor production. To some extent these results mirror the rate of stabilization observed with other parameters in the runs previously described. For example, unit 5 parameters plotted in Figure 84 show minimum stabilization and it can be observed that no gas production took place and volatile acids increased thus supporting the lead acetate-H_2S results. However, the data from Figures 81 and 82 indicate that units 2 and 3 do not clearly show that either unit stabilized more quickly than the other, but the centrifuge button test clearly shows that unit 2 stabilized faster than unit 3.

Figure 98 shows the results of the centrifuge button test for the aerobic units of Phase I. It is evident that over the first 15 days of digestion time all the sludges are fairly unstable as they discolored the lead acetate paper in 1 to 5 days. By 20 to 30 days of digestion time, however, the results show a significant stabilization has taken place for all sludges. Sludges 5A and 6A contained heat treated sludges and Stony Point sludge as seed and are amongst the slowest to be stabilized as would be expected. The only apparent reason why sludges 3A and 4A should be less stable than sludges 1A and 2A is that they had higher concentrations of solids and could produce more gas. The results achieved indicate some validity to this test procedure but much more work on the test details previously discussed in Section 6 is needed before it can be used as a reliable indicator of sludge stability. In addition, pH differences can affect the rate of H_2S evolution. The presence of nitrate will prevent H_2S formation, and the H_2S content of gas in the test chamber which produces a specific color change must be determined. Perhaps the test could be modified so that a sulfide monitor is used to directly measure the sulfide level in the gas phase. Also it should be noted that there are many other compounds which can contribute odor problems in addition to hydrogen sulfide gas, such as mercaptans, indoles and various other nitrogen and sulfur containing organics. But in general, hydrogen sulfide is the most common cause and readily identifiable odor associated with sludges and the lead acetate test shows promise as an indicator of the odor production potential of a sludge.

The anaerobic stabilization tests and parameter changes described suffer from the same deficiency as that for the aerobic stabilization, i.e., as yet there is no absolute standard of sludge stability. Thus, the parameter change with time of stabilization must be traced. A simple, easy, one-time parameter measurement or combination of measurements for assessing sludge stability was not developed.

REFERENCES

1. Veslind, P.A. "Treatment and Disposal of Wastewater Sludges", Ann Arbor Science. (1979)

2. Hartenstein, R. "Sludge Decomposition and Stabilization", Science, Vol. 212, 743-749. (1981)

3. "EPA Sludge Treatment and Disposal", Process Design Manual. (1979)

4. WPCF, "Wastewater Treatment Plant Design", Manual of Practice No. 8. (1977)

5. Rudolfs, W. "Fertilizer and Fertility Values of Sewage Sludge", Water and Sewage Works, 96, R 157 (1949)

6. Wuhrmann, K. "High-Rate Activated Sludge Treatment and Its Relation To Stream Sanitation", Sewage and Industrial Wastes, 26, 1, (1954)

7. Anderson, M.S. "Comparative Analysis of Sewage Sludges", Sewage and Industrial Wastes, 28, 132 (1956)

8. Eckenfelder, W.W. and D.L. Ford Water Pollution Control, The Pemberton Press Jenkins Publishing Company, Austin and N.Y. (1970)

9. Teletzke, G. "Wet Air Oxidation of Sewage Sludge", Process Biochemistry. (1966)

10. "Sludge Treatment and Disposal by the Zimmerman Process Twenty-Third Progress Report of the Committee on Sanitary Engineering Research of the Sanitary Engineering Division", ASCE, Vol. 85, No. SA4, 13(1959)

11. Buswell, A.M. and S.L. Neave. "Laboratory Studies of Sludge Digestion". Illinois State Water Survey Bull. 30 (1934)

12. Heukelekian, H. "Basic Principles of Sludge Digestion", in Biological Treatment of Sewage and Industrial Wastes, Vol. 2, P. 25, Reinhold Publishing Corp., N.Y. (1958)

13. Keefer, C.E. Sewage Treatment Works, McGraw-Hill Book Company (1940)

14. Fair, G.M. and K. Imhoff. Sewage Treatment, 2nd Ed., John Wiley and Sons, Inc. (1965)

EPA-287 (Cin.)
(4-76)

REFERENCES (cont'd)

15. Babbit, H.E., Sewage and Sewage Treatment, 7th ed., John Wiley and Sons, Inc. (1953)

16. McCabe, J. and W.W. Eckenfelder. Advances in Biological Waste Treatment, Pergamon Press, Inc. (1963)

17. Rudolf, W., "Gas Yield from Sewage Sludge", Sewage Works Journal, 4, 444 (1932)

18. Novak, J.T., and D.A. Carlson, "The Kinetics of Anaerobic Long Chain Fatty Acid Degradation", JWPCF, 42, 1932 (1970)

19. Sawyer, C.N., and H.K. Roy, "A Laboratory Evaluation of High-Rate Sludge Digestion", Sewage and Industrial Wastes, 27, 1356. (1955)

20. McCarty, P.L., "Kinetics of Waste Assimilation in Anaerobic Treatment", Developments in Industrial Microbiology, 7, 144, Am. Inst. Biol. Sci., D.C. (1966)

21. Woods, C.E., and J.F. Malina, "Stage Digestion of Wastewater Sludge", JWPCF, 37, 1495 (1965)

22. Maly, J., and H. Fadrus, "Influence of Temperature on Anaerobic Digestion", JWPCF, 43, 641 (1971)

23. Rankin, R.S., "Digestion Capacity Requirements", Sewage Works Journal, 20, 478 (1948)

24. Estrada, A.A., "Design and Cost Considerations in High Rate Sludge Digestion". ASCE, 86, SA3, 2479 (1960)

25. Estrada, A.A., "Anaerobic Digestion Discussion", Proceedings of a Symposium Held at Manhattan College, N.Y., (1961)

26. Downes, J.R., "Gas Collection and Sludge Heating", Sewage Works Journal, 4, 72 (1932)

27. Schlenz, H.E., "Standard Practice in Separate Sludge Digestion", Proceedings ASCE, 63, 1114 (1937)

28. Parker, D.G., C.W. Randall, and P.H. King, "Biological Conditioning for Improved Sludge Filterability", JWPCF, 44,2066 (1972)

29. Tavery, M.A., and J. Nelson, "New Problems Can Occur With Anaerobic Digestion", Water and Wastes Engineering, 16, 14 (1979)

30. Jeris, J.S., "Analysis of Anaerobic Digestion Sludge Processing and Wastewater Treatment", A Report for Cedar Creek Wastewater Treatment Facility, Nassau County Department of Public Works (1979)

REFERENCE (cont'd)

31. Unpublished Pilot Plant Monthly Data of 100% Activated Sludge Digestion conducted by County Sanitation Districts of Los Angeles County (1979)

32. Austin, S.R., J.R. Livingston, and L. Tortorici, "Waste Activated Sludge Processing", County Sanitation Districts of Los Angeles County. (1979)

33. O'Rourke, J.T. "Kinetics of Anaerobic Treatment at Reduced Temperatures", Doctoral Dissertation, Stanford Univ. Palo Alto, Ca. (1968)

34. Malina, J.F., "The Effect of Temperature on High-Rate Digestion of Activated Sludge" 16th Purdue University Industrial Wastes Conference, 232 (1961)

35. Eckenfelder, W.W. "Mechanisms of Sludge Digestion", Water and Sewage Works, 114, 207 (1967)

36. Torpey, W.N., and N.R. Melbinger "Reduction of Digested Sludge Volume by Controlled Recirculation", JWPCF, 39, 1464 (1967)

37. Torpey, W.N., "High-Rate Digestion of Concentrated Primary and Activated Sludge", Sewage and Industrial Wastes, 26,479 (1954)

38. Torpey, W.N., "Loading to Failure of a Pilot High-Rate Digester", Sewage and Industrial Wastes, 26,479 (1955)

39. Pfeffer, J.T., M.Leiter, and J.R. Worlund, "Population Dynamics in Anaerobic Digestion", JWPCF, 39, 1305 (1967)

40. Swanwick, J.D., W.J. Fisher and M.Foulkes, "Some Aspects of Sludge Technology including New Data on Centrifugation", Water Pollution Manual, Thunderbird Enterprises, Harrow, 141 (1972)

41. White M.J.D., R.C. Baskerville, and C.F. Lockyear "Continuous Thickening of Biological Sludges, and the influence of Stability" Water Pollution Control. P. 86, (1977)

42. Tebbutt T.H.Y., and M.J.D. White, "Sludge age and Stability", NATO Advanced Study Inst., University of Delaware, Newark, Delaware, (1979)

43. Dague R.R., "Fundamentals of Odor Control", JWPCF, 44,593 (1972)

44. Eikum A.S. and B. Paulsrud, "Methods of Measuring The Degree of Stability of Aerobic Stabilized Sludges" Water Research, 11,763 (1977)

45. "Standard Method of Test for Odor in Water, American Society for Testing and Materials D1292 (1975)

46. Standard Methods, 14th Edition, APHA-AWWA-WPCF. (1975)

EPA Form 2360-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 237)
☆ U.S. GOVERNMENT PRINTING OFFICE: 1980-660-939
TYPING GUIDE SHEET

REFERENCES (cont'd)

47. Ruffer, H. (1966) "Untersuchunger Zur Characterisierung Aerob Biologisch Stabilisierter Schlamme", Vom Wasser, Band 13 pp. 255-282 (From Eikum A.S. 1973, ph.D Thesis)

48. Schepman B.A., and C.F. Cornell, "Fundamental operating Variables in Sewage Sludge Filtration", Sewage and Industrial Wastes, 28, 1443 (1956)

49. Halff, A.H., "An Investigation of The Rotary Vaccuum Filter Cycle as Applied to Sewage Sludges", Sewage and Industrial Wastes. 24,962 (1952)

50. Trubnick, E.H., and P.K. Mueller, "Sludge Dewatering Practice", Sewage and Industrial Wastes. 30,1364 (1958)

51. Burd, R.S., "A Study of Sludge Handling and Disposal", Water Pollution Control Research Series, Publication WP-20-4.

52. Bennett, E.R., D.A. Rein, and K.D. Linstedt, "Economic Aspects of Sludge Dewatering and Disposal" ASCE. 99,55 (1973)

53. Morris, R.H., "Polymer Conditioned Sludge Filtration", Water and Wastes Engineering, 2,68 (1965)

54. Albertson, O.E., and E.J. Guidi, "Advances in The Centrifugal Dewatering of Sludges", Water Works and Wastes Engineering, R-133 (1967)

55. Parker, D.C., C.W. Randall, and P.H. King, "Biological Conditioning for Improved Sludge Filterability", JWPCF, 44,2067 (1972)

56. McKinney, R.E., H.E. Langley and H.D. Tomlinson, "Survival of Salmonella Typhosa During Anaerobic Digestion", Sewage and Industrial Wastes, 30,12 (1959)

57. Peterson, J.R., C. Lue-Hing, and D.R. Zeng, "Chemical and Biological Quality of Municipal Sludge", in Recycling Treated Municipal Wastewater and Sludge through Forest and Cropland, W.E. Sopper and L.T. Kardos, Eds. (University Park, PA: Pennsylvania State University Press) (1973)

58. Palfi A. "Survival of Enterovirus during Anaerobic Sludge Digestion", Proc. 6th Int. Wat. Pollut. Res. Conf. (1972)

59. Eisenhardt, A., E. Lund, and B. Nissen, "The Effect of Sludge Digestion on Virus Infectivity". Water Research, 11, 579 (1977)

60. Bertucci, J.J., C.Lue-Hing, D. Zeng, and S.J. Sedita, "Inactivation of Viruses during Anaerobic Sludge Digestion" JWPCF, 49, 1642 (1977)

61. Sanders, D.A., J.F. Malina, Jr. B.E.Moore, B.P. Sagik, and C.A. Sorber, "Fate of Poliovirus during Anaerobic Digestion". JWPCF, 51, 333 (1979)

REFERENCES (Cont'd)

62. Moore, B.E. et al, "The Effect of High Rate Anaerobic Digestion on Viruses." Paper presented at 49th Annual Conf., WPCF, Minneapolis, Minn. (1976)

63. Ward, R.L. and C.S. Ashley, "Inactivation of Poliovirus in Digested Sludge." Applied Environ. Microbiol., 31, 921 (1976)

64. Dorcey, A.H.J. and R.S. Howe, Public choice and the land application of municipal wastewaters and sludges. In: Risk Assessment and Health Effects of Land Application of Municipal Wastewaters and Sludges, B.P. Sagik and C.A. Sorber, eds. Center for Applied Research and Technology, The University of Texas at San Antonio. pp. 303-324. (1978)

65. Geldreich, E.E., "Bacterial populations and indicator concepts in feces, sewage, stormwater and solid wastes" 51-97, In: "Indicators of viruses in water and food" edited by Berg, G., Ann Arbor Science (1978)

66. Englande, A.J., "Fate of Parasites and Viruses". NATO Advanced Study Institute Univ. of Delaware (1979)

67. Liebmann H., "Parasites in Sewage and the possibilities of their extinction". Adv. in Wat. Pollution Res. Proc. 2nd Int. Conf., 269, (1964)

68. Hays, B.D., "Potential for Parasitic Disease Transmission with Land Application of Sewage Plant Effluents and Sludges". Water Research, 11, 583 (1977)

69. Cram, E.B. "The Effect of Various Treatment Processes on The Survival of Helminth Ova and Protozoan Cysts in Sewage". Sewage Works Journal, 15, 1119 (1943)

70. Ruchhoft, C.C., "Studies on the Longevity of Bacillus Typhosus in Sewage Sludge". Sew. Works Jour. 6, 1054 (1934)

71. McKinney, R.E., H.E. Langley, and H.P. Tomlinson, "Survival of Salmonellae Typhosa During Anaerobic Digestion" Sew. and Ind. Wastes, 30, 1469 (1958)

72. Mom, C.P., and C.O. Schaeffer, "An investigation into the Hygienic Significance of Sewage Purification in the Tropics in Regard to Typhoid Fever". Sew. Works Jour., 12,715 (1940)

73. Kabler, P. "Removal of Pathogenic Microorganisms by Sewage Treatment Processes". Sew. and Ind. Wastes, 31, 1373 (1959)

74. Cooke, M.B., E.L. Thackston and G.W. Malaney, Water and Sewage Works, 50, 125 (1978)

EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 267)
U.S. GOVERNMENT PRINTING OFFICE 1980-660-059
TYPING GUIDE SHEET

REFERENCES (Cont'd)

75. Ahlberg, N.R., and B.I. Boyko, "Evaluation and Design of Aerobic digesters". JWPCF, 44,634 (1972)

76. Koers, D.A., and D.S. Mavinic, "Aerobic Digestion of Waste Activated Sludge at low Temperatures". JWPCF, 49,460 (1977)

77. Hartman, R.B., D.G. Smith, E.R. Bennett, and K.D. Linstedt, "Sludge Stabilization through aerobic digestion". JWPCF. 51, 2353 (1979)

78. Eikum, A.S. "Aerobic Stabilization of Primary and Mixed Primary/Chemical (Alum) Sludge" Ph.D Thesis. University of Washington (1973)

79. Hartman, R.B., E.R. Bennett, and K.D. Linstedt, "New Procedure Determines Aerobic Sludge Stability". Water and Sewage Works. p. 42 (1978)

80. Viraraghavan, V. "Digesting sludge by aeration", Water Works and Wastes Engineering 2, Sept. 1965.

81. Eckenfelder, W.W., Jr. and C.J. Sathanam, "Sludge Treatment", Chapter 8, Marcel Dekker, Inc., New York (1981)

82. "Secondary and Tertiary Treatment", Manhattan College Summer Institute Course Text, Chapter I (1981)

83. Reynolds, T.D. "Aerobic Digestion of Thickened Waste Activated Sludge." Proceedings 28th Purdue Industrial Waste Conference. Purdue University, Lafayette, Indiana (1973)

84. Jaworski, N., G.W. Lawton, and G.A. Rohlich "Aerobic Sludge Digestion". Int. J. Air and Water Poll. 4,106 (1961)

85. Patterson, J.W., P.L. Breznick, and H.D. Putnam, "Measurement and Significance of Adenosine Triphosphate in Activated Sludge" Environmental Science & Technology, 4, 569 (1970)

86. Brezonik, P.L., and J.W. Patterson, "Activated Sludge ATP-Effects of Environmental Stress" ASCE, SA6, 8-13 (1971)

87. Weddle, C.L., and D. Jenkins, "The Viability and Activity of Activated Sludge". Water Research, 5, 621 (1971)

88. Haug, R.T., "Sludge Processing to Optimize Digestibility and Energy Production" JWPCF 49,1913 (1977)

89. Haug, R.T., D.C. Stuckey, J.M. Gossett, and P.L. McCarty, "Effect of Thermal Pretreatment on Digestibility and Dewaterability of Organic Sludges". JWPCF, 50,73 (1978)

90. Brooks, R.B., "Heat Treatment of Activated Sludge", Water Pollution Control, 67, 592 (1968)

EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 247)
© U.S. GOVERNMENT PRINTING OFFICE 1980-660-638
TYPING GUIDE SHEET

REFERENCES (Cont'd)

91. Marshall, D.W., W.J. Gillespie, "Comparative Study of Thermal Techniques for Secondary Sludge Conditioning", Proceedings of the 29th Ind. Waste Conf., Purdue Univ. Press, Ind., 589 (1974)

92. Brooks, R.B., "Heat Treatment of Sewage Sludge", Water Pollution Control, 69, 92 (1970)

93. McCarty, Perry, Lilly Y. Young, Joseph B. Healy, Jr., William F. Owen, and David C. Stuckey. "Thermochemical Treatment of Lignocellulosic and Nitrogenous Residuals for Increasing Anaerobic Biodegradability", Annual Fuels from Biomass Symp. 2nd Proc., p. 787-821. (1978)

94. Lebrun, T.J. and L.D. Tortoric, LA/OMA Thermal Treatment Anaerobic Digestion Study. July, 1978. Study conducted by Research Section County Sanitation Districts of Los Angeles.

APPENDIX

Tabulation of Copyright Holders Who Granted Permission to Reproduce the Tables and Illustrations Indicated

Illustration (TABLE)	Page	Literature Citation	Copyright Holder
8	17	31	Los Angeles County Water Pollution Control Districts
9	18	32	Los Angeles County Water Pollution Control Districts
11	31	41	Water Pollution Control Federation
12	31	41	Water Pollution Control Federation
13	32	42	University of Delaware
14	32	42	University of Delaware
15	34	1	Ann Arbor Science Publishers
16	40	50	Water Pollution Control Federation
23	47	64	University of Texas
24	47	65	Ann Arbor Science Publishers
25	48	61	Water Pollution Control Federation
27	54	68	Pergamon Press
28	55	1	Ann Arbor Science Publishers
30	63	78	University of Washington
(FIGURE)			
1	5	2	American Association for the Advancement of Science
2	5	23	Water Pollution Control Federation
3	13	25	Manhattan College
4	19	32	Los Angeles County Water Pollution Control Districts
5	20	22	Water Pollution Control Federation
6	22	33	Stanford University
8	25	39	Water Pollution Control Federation
9	25	22	Water Pollution Control Federation
13	29	40	Water Pollution, Harrow, England
14	35	48	Water Pollution Control Federation
15	36	52	American Society of Civil Engineers
17	39	52	American Society of Civil Engineers
18	39	59	Pergamon Press
19	39	59	Pergamon Press
20	49	61	Water Pollution Control Federation
21	50	61	Water Pollution Control Federation
22	51	61	Water Pollution Control Federation
25	56	75	Water Pollution Control Federation

Illustration (FIGURE)	Page	Literature Citation	Copyright Holder
26	58	76	Water Pollution Control Federation
27	59	77	Water Pollution Control Federation
28	61	44	Pergamon Press
29	62	44	Pergamon Press
30	62	44	Pergamon Press
32	65	77	Water Pollution Control Federation
33	66	77	Water Pollution Control Federation
34	67	77	Water Pollution Control Federation
37	71	82	Manhattan College
39	73	83	Ann Arbor Science Publishers
40	73	84	Pergamon Press
41	74	76	Water Pollution Control Federation
44	78	84	Pergamon Press
45	79	84	Pergamon Pres
46	80	78	University of Washington
47	81	77	Water Pollution Control Federation
48	83	78	University of Washington
49	85	90	Water Pollution Control Institute, England
50	87	90	Water Pollution Control Institute, England
51	88	90	Water Pollution Control Institute, England
52	88	91	Ann Arbor Science Publishers
53	90	92	Water Pollution Control Institute, England
54	91	92	Water Pollution Control Institute, England
55	92	92	Water Pollution Control Institute, England
56	93	92	Water Pollution Control Institute, England
57	94	92	Water Pollution Control Institute, England